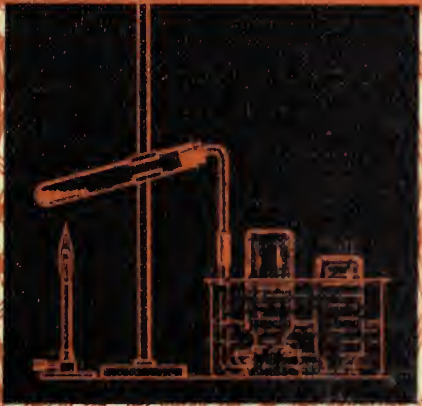
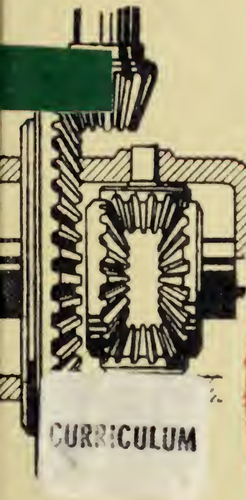
BASIC PHYSICAL SCIENCE





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BASIC
PHYSICAL SCIENCE

D. VAN NOSTRAND COMPANY (CANADA), LTD.
PRINCETON / TORONTO / LONDON

BASIC
PHYSICAL SCIENCE

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120 Alexander Street, Princeton, New Jersey
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D. Van Nostrand Company, Ltd.
358 Kensington High Street, London, W. 14, England

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Preface

Today it is taken for granted that science should be part of the stock-in-trade of an educated person and it is generally agreed that science should be an essential part of the hard core of a school curriculum. Any differences of opinion concern the nature of the science courses. What should be their content at the various levels? It is apparent that a science course at any level should be part of a pattern designed to acquaint the student with the nature of the universe and with the way nature behaves. Such a pattern cuts across many branches of science—physics, chemistry, biology, geology, astronomy, and meteorology. It should therefore stress the interdependence of these sciences and the unity of the whole. This textbook presents that part of the pattern suitable for Grade Nine.

The science courses before Grade Nine are largely descriptive and nonmathematical. But now is the time to delve a little deeper, to look for reasons, and even to express some of our findings in simple mathematical language. This particular course cuts across physics and chemistry. Its main theme is energy—mechanical energy, chemical energy, heat energy, light energy and, finally, the transformation of chemical energy into the energy of motion.

Unit I, the introductory unit, describes the methods of science, particularly the experimental method.

It is in Unit II (Machines at Work) that the pattern begins to unfold. This is the story of force, work, power, energy, and energy transformation, as applied to simple machines; it is the basic unit in the course. The concepts discussed in this unit are frequently referred to in the later units. Indeed, an understanding of the later units depends upon the fundamental concepts of energy and its transformations as outlined in Unit II.

Unit III (The Combustion of Fuels) deals with the transformation of chemical potential energy into heat energy. This important theme will be emphasized in later science courses. But let it be said that the most spectacular examples of such transformations result in burning—the burning of hydrogen, of coal, of oil, of natural gas. All these are discussed in Unit III.

Unit IV (Heat and Temperature) attempts to answer some of the questions that inevitably arise in Unit III. When fuels combine with oxygen a flame is produced. A flame is hot. What is meant by the word *hot?* What is heat? And how does heat differ from temperature? In Unit IV heat and temperature are explained (and distinguished from each other) in terms of the kinetic theory which was discussed in Unit I.

Unit V (Light) is a natural outcome of Units III and IV. Not only is a flame hot but it gives light. Thus, in the burning process, chemical potential energy is transformed into heat energy and light energy; light is inevitably associated with heat.

What is light? And what are some of its effects? What is color? These are some of the questions answered in Unit V.

Unit VI (Transportation) is again a natural outcome of Units II and III. When a fuel burns, heat energy is released. By suitable devices (such as a steam engine or an internal combustion engine) this heat energy can be transformed into kinetic energy. Thus it is that man has developed various ingenious means of locomotion; first the steam locomotive, then the automobile and, finally, the airplane. But this is by no means the end of the trail. Using the same energy transformation, he has invented rockets capable of encircling the earth and even the sun. His next goal is the space-ship that will take him to the moon.

The above outline, however, is no mere description of scientific phenomena. The method of teaching the course is equally important. The method of teaching should be closely allied to the way scientific information is obtained. The scientific method makes sense; it is a way of life; it is a natural approach to many everyday problems. The teaching of science differs from the teaching of other subjects in that it readily lends itself to the experimental approach. This textbook employs the experimental approach whenever it is practicable. That is to say, a new concept is usually introduced by a suitable experiment and, from the observations made by the students, knowledge is acquired.

This is an exciting way of learning; or, it may be better to say that it can be an exciting way of learning. But it is not without pitfalls. An experiment that "misfires" is worse than no experiment at all; it may even lead to the wrong conclusions. In short, the experimental way of teaching and learning depends upon experiments that work. All the experiments described in the textbook will work if instructions are followed. Some, however, need a little skill in manipulation. It is therefore strongly recommended that, whenever possible, the experiments be tested before the class period. By so doing, the teacher will have confidence in the outcome and, equally important, he can intelligently discuss with his class the various steps in the procedure and even invite his students to predict an outcome before the experiment is tried.

The authors wish to acknowledge the help and assistance they have been given by the following people in Alberta: Mr. N. A. M. Knowles and Mr. R. A. Roberts, science teachers; Mr. C. Hampson and Mr. S. Norris, Faculty of Education, University of Alberta; Mr. H. A. Pike and Mr. H. R. Ross, superintendents of schools; Mr. R. A. Shaul, Supervisor of Junior High Schools, Edmonton Public School Board; and Mr. A. B. Evenson, Department of Education, Edmonton. By guidance, consultation, and the critical reading of the manuscript these teachers have aided the authors greatly.

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UNIT

I

Introductory

USAF

I

What Is Science?

The word "science" is derived from the Latin word *scientia,* which means knowledge or learning. Then, one might ask, is all knowledge scientific knowledge? The answer, of course, is "no." Science has come to mean a special kind of knowledge —a knowledge of nature and the way nature behaves. Thus we can say that every scientist is, in a sense, grappling with nature, trying to discover the "secrets" of nature. When a "secret" of nature has been discovered, we call it a scientific fact or, sometimes, a scientific law. We shall refer to a number of scientific laws in the course of our reading. But we must remember that a scientific law is simply a statement of the way nature behaves. A man-made law, on the other hand, is made by a government for our protection in society; it is something we must obey. But man cannot make or change scientific laws; he can only discover them.

How Is Scientific Knowledge Used?

Suppose plans are made to build a new steel bridge, and suppose the length of the bridge is known. The engineer who designs the bridge can tell you how much the bridge will expand between a low winter temperature and a high summer temperature. He knows the answer without having to build a bridge to try it out. How does he know? The rate at which steel expands has been measured and tabulated. This is a scientific fact. The engineer knows that steel will always expand by a certain amount when heated through a known temperature, and he can use this knowledge, confident that further experimental tests are unnecessary.

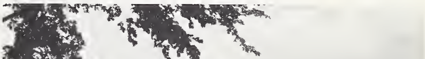

Fig. 1-1. In designing a steel bridge an engineer uses known facts on expansion to compute the maximum expansion of the bridge in summer and its maximum contraction in winter.

How Is Scientific Knowledge Obtained?

Suppose you lift a fairly big rock from the bed of a shallow pond. The first thing you notice is that the rock seems lighter than you had expected. This is because you have been accustomed to lifting rocks in air, not in water. Now suppose you lift the rock out of the water. The rock seems to be heavier; and indeed it is, much heavier. And so this single experiment (and it *is* an experiment) seems to indicate that stones or rocks weigh less in water than in air. We are now on the way to an important discovery. Of course, a single experiment does not tell us anything for certain. We must repeat the experiment with other objects besides rocks, and we must immerse the objects in shallow water and deep water, in fresh water and sea water, and in other liquids such as alcohol or gasoline. In all cases we find that *any* object immersed in *any* liquid weighs less than it does in air. Once we have established this scientific fact or generalization, we can depend upon it to happen always; we know it is one of the ways nature behaves. Indeed, you may have so much faith in "nature" that you are willing to take a risk. If you lie relaxed on the surface of a calm sea, you will find that water will buoy you up so much that you even float!

We now begin to understand how scientific knowledge is obtained. First of all, we can say that we get information through experiment; or, expressing it another way, information on the way nature behaves is obtained through the use of our senses (such as seeing, touching, hearing). But scientific knowledge usually depends on more than mere experimental facts; a process of reasoning is also involved. For example, we now know that any object appears to weigh less in water than in air. But this is only the beginning of an investigation—there are many other things we want to know. Does the weight lost by an object depend on its weight or its volume? Do all objects of the same volume appear to lose the same weight when immersed in water?

These questions will be discussed in a later chapter, and we shall obtain the answers simply by a combination of experiment and reasoning.

What Are Some Examples of Scientific Discovery?

To answer this question it may be well to discuss briefly certain scientific discoveries made by three different scientists. In this way we shall see what each scientist had in mind and how he attacked his particular problem. The men we shall consider are Davy, Hall, and Rutherford. These scientists worked in entirely different fields and at different periods of time; Davy did his work in the early nineteenth century, Hall in the late nineteenth century, and Rutherford in the early twentieth century.

Sir Humphry Davy

Humphry Davy was one of the outstanding British scientists in the early part of the nineteenth century. He was both a physicist and a chemist, and he had made notable discoveries in both fields. Davy lived when the industrial revolution in England was taking place. The industries of England were founded upon the power

Fig 1-2. Sir Humphry Davy (1778–1829) invented a safety lamp which reduced explosions in coal mines.

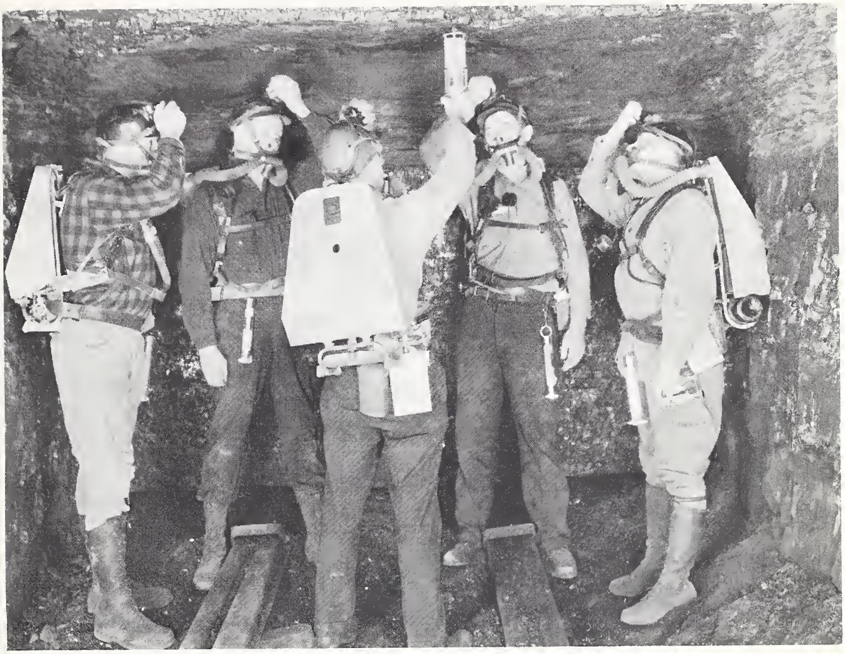

Fig. 1-3. A crew testing for explosive firedamp in a coal mine by examining the flame of a Davy lamp. Notice that the men are blocking off the light from the light bulbs on their helmets.

of coal. But, although coal was very abundant, the methods of mining it were very crude. For example, every coal miner had to provide his own light at the coal face. The source of light was usually a candle made from sheep's fat. But a candle flame is a "naked flame," and a naked flame is dangerous in the presence of the flammable gases often found in coal mines. Therefore, it is not surprising that serious explosions occurred from time to time. During the years 1810 to 1815, the explosions were so frequent and the loss of life so heavy that the mine owners decided to seek the help of a scientist and appealed to Humphry Davy. What could be done to make the mines safe for the workers?

Davy accepted this appeal as a challenge, as a scientific problem to be solved. He realized that if the burning gas could be prevented from spreading throughout the mine, there would be no explosion. How could this be done? Working with a flame of coal gas he tried many experiments—but the experiment that solved the problem was the simplest of all. He discovered that if a piece of copper gauze is lowered onto a flame, the flame is "pushed down"; the gas burns below the gauze but not above it. (See page 152 for a description of the experiment.) The gauze cools the gas so that the flame does not pass through the gauze. Having discovered this simple fact, Davy proceeded to build an oil lamp with a protecting screen of copper gauze (see Fig. 1-4). The lamp worked; it was safe to use in mines. (We shall make a further reference to it in a later chapter.) It is said that Davy spent only three or four weeks in solving this problem, but in doing so he saved many hundreds of lives.

It is interesting to note that although the "Davy Safety Lamp" was used by hundreds of thousands of miners, Davy received no financial reward for his invention. Had he taken out a patent on the lamp he would have been a wealthy man. His outstanding contribution to scientific knowledge, however, did not pass unrecognized, for in 1812 Davy received a knighthood. But the real reward for the scientist is the discovery of knowledge; Sir Humphry Davy's satisfaction came from the solving of a scientific problem and its benefit to mankind.

You probably know that coal miners no longer use a Davy lamp as a source of light. Instead, an electric light with a dry cell is usually attached to the miner's helmet. However, the Davy lamp is still used to detect pockets of flammable gas in a mine.

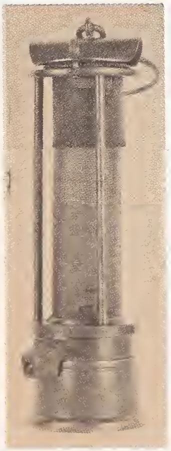

Fig. 1-4. Davy's safety lamp.

Charles Martin Hall

From earliest times, even as early as 1000 B.C., man has known how to obtain iron from iron ore. As you may know, iron is now made by heating iron ore with coke (which is a form of carbon) in a blast furnace. This iron is then made into steel which is used in ships, bridges, and skyscrapers.

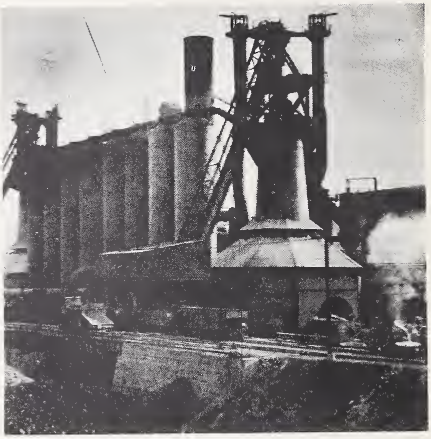

Fig. 1-5. A blast furnace in operation. On the left of the furnace are eight stoves for heating compressed air. A skip car carries iron ore and coke up the inclined track to the top of the furnace. Notice that molten slag is running into a ladle on the right of the picture.

One of the advantages of steel is its great strength; one of its disadvantages is its "heaviness" or, as we usually say, its high density. Aluminum is much lighter than steel, and it can be made almost as strong. Moreover, aluminum ores are much more abundant than iron ores. Then why not use aluminum in place of steel for some constructional work? This was one of the questions asked by scientists in the nineteenth century; indeed, the question posed a problem which many scientists tried to solve.

Aluminum occurs with other elements in clay and, particularly, in a mineral called bauxite. It was easy to obtain a white substance called aluminum oxide (or alumina) from bauxite. The real problem was to obtain aluminum from alumina (or aluminum oxide). How could this be done? The first obvious step was to try the "iron method"; that is, to heat alumina with coke. This was done—and nothing happened. In other words, hot coke (or carbon) is unable to decompose alumina (or to break

Fig. 1-6. Charles Martin Hall.

the chemical bonds between aluminum and oxygen). The next step was to try "stronger" chemicals than coke. Alumina was heated with the metal potassium, and a bright silvery button of aluminum was obtained. The more powerful chemical worked. But aluminum made this way was very expensive. It cost about a hundred and fifty dollars a pound; it was more expensive than silver and therefore unsuitable for construction work. The question remained–how could aluminum be made cheaply enough to compete with steel?

About this time (in 1880) a professor of chemistry in Oberlin College, Ohio, U.S.A., discussed the aluminum problem with his chemistry class. He pointed out the chemical difficulties in obtaining aluminum on a large scale and, at the same time, described the wide range of uses that awaited the new metal. His remarks inspired one of his students named Hall to "go after the new metal."

Hall began work on this project while still an undergraduate at Oberlin. Because the coke method had failed, it was apparent that an entirely new method of extracting metals had to be devised. Could alumina be split up by electricity? Hall found that an electric current would melt and decompose alumina but, in the process, the metal aluminum became so hot that it boiled away. At least he was on the right track, but what was the next step?

Hall now set out to find a mineral which would melt at a much lower temperature than alumina and in which alumina would dissolve. There followed a long and tedious task of testing various minerals, and his work was far from complete when he graduated from college. Undaunted, he continued his work at home in Oberlin, using his father's woodshed as his laboratory. Finally, in 1886, success came. The mineral that achieved the desired effect was cryolite, which is found only in Greenland. Cryolite melts at a lower temperature than alumina. When a current flows, alumina dissolves and is decomposed. Molten aluminum collects at one of the cell terminals immersed in the cryolite. This was success indeed; it gave Hall fame and fortune.

The Hall process is still the method employed to extract aluminum metal from alumina. In the vast aluminum plant at Kitimat in British Columbia, electricity, obtained from water power, is used to melt cryolite and decompose alumina, just as Hall did it almost three-quarters of a century ago. Today we see the effects of Hall's discovery everywhere. Aluminum kitchenware is found in every home; the bodies of

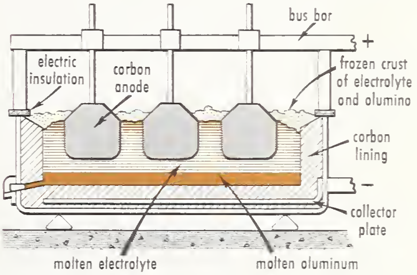

Fig. 1-7. The Hall electrolytic process for manufacturing aluminum. Aluminum escapes through the outlet on the left and is collected in a ladle.

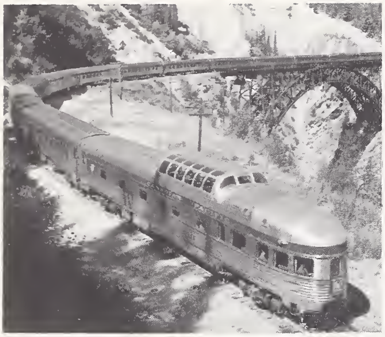

Fig. 1-8. This modern streamlined passenger train is made of aluminum.

Fig. 1-9. Lord Rutherford.

airplanes and modern railroad coaches are constructed largely of aluminum; towers supporting high tension lines are often made of aluminum; aluminum wire is sometimes used instead of copper wire to conduct an electric current. You can probably think of many other uses for aluminum.

Lord Rutherford

It is generally agreed that one of the most eminent scientists in the first half of the twentieth century was Ernest Rutherford. How did he come to be a scientist? Rutherford was the son of a New Zealand farmer, a "settler" from Scotland. He showed unusual native ability in the primary school and won scholarships to a secondary school and, later, to college. He graduated from his college in New Zealand with highest honors in mathematics and physics, a distinction that led to the award of a fellowship in Cambridge University, England. There Rutherford pursued with distinction his graduate studies in physics and, in 1898, when only twenty-eight years of age, was appointed head of the department of physics in McGill University, Montreal.

He stayed at McGill for eight years, continuing his research and making many remarkable discoveries, chiefly in radioactivity. From McGill he went to Manchester University in England, as head of the physics department. In 1919 he was appointed director of the famous Cavendish Laboratory in Cambridge and remained there until his death in 1937. Why is Rutherford regarded as one of the most eminent of all scientists?

Rutherford was a pioneer in the field of atomic structure. He gave us the first model of the modern atom with its tiny nucleus of protons surrounded by electrons. Rutherford was a born experimenter. Although he dealt with particles too small to be seen through the most powerful microscope, he devised experiments to show the effects of these particles. It was his rare combination of ingenuity and experimental skill that made him the acknowledged leader in this new field, a field that has developed at a remarkably rapid rate in the space of about forty years.

It is not surprising that Rutherford was the leader of a group of scientists that first split the atom. Or, it may be more accurate to say that the first experiment in which an atom was split was carried out by two of Rutherford's research students (Cockcroft and Walton) in the Cavendish Laboratory in 1932.

The outstanding work of Rutherford was recognized during his lifetime, and honors were showered upon him. He received honorary degrees from many British and foreign universities, and he was awarded the highest of all academic distinctions—a Nobel prize. Nor was his country slow to recognize his monumental contributions in the field of modern physics. First, he received a knighthood, and in 1931 he was raised to the peerage.

What Are the Characteristics of a Scientist?

Let us now briefly compare and contrast the procedures of our three scientists. All three were experimenters; they made careful observations through their experiments. These observations were scientific discoveries closely related to their problems. In all cases they set out with a particular problem in mind. Notice that Davy's problem was most easily solved; he found his answer in three or four weeks. Hall, on the other hand, did not solve his problem for four or five years. And Rutherford worked in a vast new field; no sooner had he solved one problem than other closely related problems came up. He spent his whole academic life grappling with new problems on the frontiers of knowledge. Persistence in the face of failure is characteristic of all great scientists.

Notice also that our three scientists illustrate three different contributions of scientific endeavor. Davy's work was directed toward solving a problem that led to the relief of human misery. Similar ideals have inspired other scientists to seek and make chemicals with which to fight infection and disease, chemicals such as the sulfa drugs and other antibiotics. Hall's work, also of a practical nature, has resulted in more physical comforts for us. It is akin to research work on plastics, the new fibers like nylon, synthetic rubber, or even new detergents. But Rutherford's work at first appeared to have no practical application; yet it offers the most promise to mankind as a whole. Because Rutherford was curious about atoms and particles smaller than atoms, scientists have now learned of the vast stores of energy locked up within an atom, and great progress is being made in the controlled release of it. The time is not far distant when nations without coal or oil will derive energy from atoms so that they too will have power to develop their industries.

A Scientific Method in School

All that has been said about the ways of a scientist applies even when you first begin to study science. You too can find answers to many questions by doing experiments. Every experiment teaches something; it reveals something worth knowing; it teaches a scientific fact. It is the only satisfactory way in which we can accumulate scientific knowledge. We shall perform a large number of experiments in the course of our reading; in this way we shall make discoveries and extend our scientific knowledge.

Things to Remember

Scientific knowledge is knowledge of the way nature behaves.

Scientific knowledge is usually acquired by observing experiments and reasoning about them.

Questions

1. What is the difference between a scientific law and a man-made law?
2. Water freezes in winter; molten steel solidifies on cooling. Express these two facts as a single generalization, or scientific law.
3. What was Davy's safety lamp?

4. Describe briefly the particular problem that Davy had to solve in making his safety lamp.
5. What is the main difference between the process for making [**a**] iron, [**b**] aluminum?
6. Describe briefly one of Hall's problems in working on his aluminum process, and explain how he solved the problem.
7. Which of the scientists–Davy, Hall, or Rutherford–made the greatest scientific contribution? Why?
8. Do scientists do experiments to make our way of life easier or because they want to discover more of the secrets of nature?

UNIT
II
Machines at Work

2

Measurements of Length and Weight

Every scientist needs tools and equipment to do his job, to give him the information he seeks. He usually refers to his tools and equipment as apparatus and, in a modern laboratory, the apparatus is often very complicated. Apparatus is also needed for the simple experiments we shall perform in the school laboratory. You are probably already familiar with such things as test tubes, beakers, flasks, Bunsen burners, rulers, and balances.

In collecting accurate information the scientist is concerned with accurate methods of measuring and weighing. And so are we. Even from earliest times scientists have realized that measurements form the basis of constructional work. Before discussing this problem, let us consider a simple example of measurement, one we can easily do for ourselves in the classroom.

Experiment

2-1. To measure an object with a ruler

First, examine a ruler (see Fig 2-1) and observe that it is divided into inches along one edge and into centimeters along the other. Notice that the inches are divided in halves, quarters, eighths, and sixteenths. In other words, we can measure the length of an object to a sixteenth of an inch. Notice, also, that the centimeters are divided into tenths so that, if we wish, we can also measure a length to a tenth of a centimeter.

Measure the length of the cover of your science text book in inches and in centimeters, and from these measurements calculate the number of centimeters in an inch. Suppose, for example, the length is $9\frac{7}{16}$ inches (usually written $9\frac{7}{16}$ in.) and

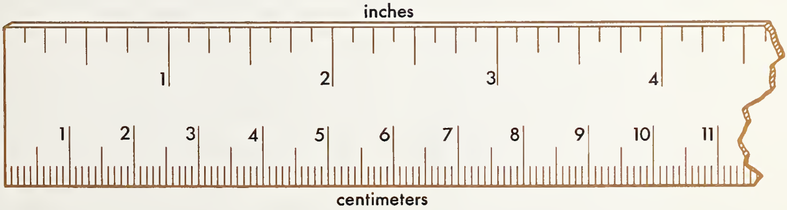

Fig. 2-1. Diagram comparing the centimeter scale with the inch scale.

also 23.9 centimeters (usually written 23.9 cm.). To find the number of centimeters in an inch we must, of course, divide 23.9 by $9\frac{7}{16}$. You should solve this problem yourself. The answer is 2.54. Or, we could find the number of inches in a centimeter. The answer, in this case, is $\frac{9\frac{7}{16}}{23.9} = 0.394$. You will find it useful to remember that there are approximately 2.5 centimeters in an inch, and that one centimeter is approximately equal to 0.4 of an inch.

Methods of Weighing Objects

Before discussing the units of length and weight in detail, it may be well to consider some of the methods of weighing various objects. Instruments for weighing are in general more complicated than those for measuring length. One such instrument is a spring balance (see Fig. 2-2). In using this instrument the object to be weighed is suspended from the hook of the balance; the spring is thereby stretched, a pointer moves over a scale and comes to rest, indicating the weight of the object.

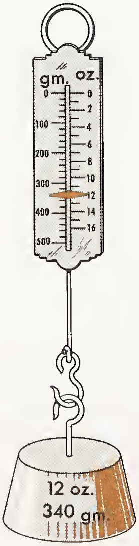

Fig. 2-2.
A spring balance.
A pointer moves
over a scale
and indicates
the weight of
the object.

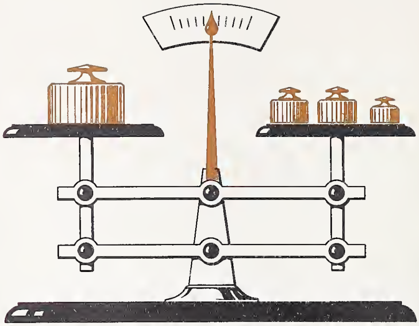

Fig. 2-3. Equal weights only balance the scale.

A pan balance (or equal-arm balance) is a more accurate instrument for determining weight. It consists of a beam supported on a knife-edge at its midpoint, and pans at both ends of the beam for holding the object and balancing weights. The object to be weighed is placed on the left pan, and standard weights are added to the right pan until a balance is restored (see Fig. 2-3).

Experiment

2-2. To weigh an object by a spring balance and also by an equal-arm balance

Weigh an object such as a piece of metal on a spring balance. (An object weighing 200 grams is suitable.) Read the position of the pointer as accurately as possible.

Now, using an equal-arm balance, place the object on the left pan and add weights to the right pan until balance is restored. Add up the weights on the right pan to give the weight of the object. Does each instrument record the same weight?

Mass and Weight

The mass and weight of a body are quite different concepts and yet they are often measured by the same units. Thus a body may have a weight of 2 pounds and also a mass of 2 pounds. What is the difference between weight and mass? The *weight* of a body refers to the gravitational attraction of the earth upon the body; its *mass* refers to the quantity of material in the body.

What does the spring balance measure, mass or weight? The earth pulls the body downward and the spring exerts an equal and balancing force upward. That is to say, the spring balance measures weight—the pull of gravity. If the body were taken by rocket some hundreds of miles above the earth, the earth's attraction for the body would be less (why?), and therefore the reading of the spring balance would also be less than 2 pounds. However, the quantity of matter has clearly not changed—the body still contains 2 pounds of matter. We see, therefore, that mass and weight can be expressed by the same quantity (for example, 2 pounds) as long as the body is on the earth's surface (and near sea level) but not otherwise.

And, finally, it should be observed that when an equal-arm balance is used, the attraction of the earth on the body is the same as the earth's attraction on the weights. Thus the two effects neutralize each other. If the pan balance were taken by rocket several hundred miles above the earth's surface, would the balance reading be less than 2 pounds? The earth's attraction for both the body and the weights in the pan would be reduced by the same amounts so that measurements on the pan balance would not be affected by altitude. In other words, a pan balance indicates the mass of an object compared with the masses of the weights.

Units of Length and Weight

And now to return to the ruler. The markings on the ruler indicate that there are two entirely different systems for measuring length. Why two? Would it not be simpler to have only one system? Before answering these questions it may be well to refer briefly to the historical development of these units.

Even in early civilizations, neither constructional work nor trading could be carried on without a system of weights and measures. The Pyramids in Egypt were built at least 3000 years ago, from stone cut exactly to size. Present-day engineers are amazed at the accuracy of the constructional work in many ancient monuments such as the Pyramids. What was the standard of measurement in these ancient times? Actually, the Egyptians, the Hebrews, the Romans, the Greeks, and the early English all had their own independent units of measurement. The bases for some of their measurements were the lengths of various parts of the body, and some of their terms we still use to this day.

One of the oldest units of length is the *inch*. The original inch was the distance from the top of a man's thumb to the first joint; it was used to mark off short distances. The length of the *foot* was used to pace off longer distances. A still longer distance was the length of the forearm; it was called a *cubit*, a term frequently referred to in the Bible. And, finally, the length of the outstretched arm was called a *yard*. This particular unit of lengths was introduced by the English in the twelfth century A.D. or thereabouts.

It is apparent that these "standards" were pretty rough and ready. They varied so much, even in a given country, that standards had to be fixed by law. These standards were useless for comparing measurements in physics and chemistry made in different countries. International scientific co-operation was out of the question until there was international agreement on the acceptable standards of weights and lengths.

The British System of Units

So far we have referred only to units of length. But precisely the same arguments apply to units of weight. The earliest English weight was the *pound*, a term used in Saxon times. The present English systems of lengths and weights with their inches, feet, yards, pounds, and tons were adopted in England in the thirteenth century. The yard became the official unit of length and the pound the official unit of weight. It was obviously necessary to have reference

– Inch and Foot –
Three barley corns taken from center of ear placed end to end equals one inch.
(Edward II 1324)
A foot ranged from 9¾ inch to 19 inches

– Yard –
King Henry I decreed.
The distance from the point of his nose to the end of his thumb was the lawful yard.

– Cubit –
First known measurement.
About 20 inches.
Length of forearm from point of elbow to end of the middle finger.

Fig. 2-4. Foot. Yard. Cubit.

standards for these basic units, the yard and the pound. These official standards are kept in the Standards Office of the Board of Trade in London, England. The imperial yard, for example, is the distance between two lines on a bronze bar at a certain temperature (62°F). The imperial pound is the mass of a cylinder of platinum of certain dimensions. Exact duplicates of the standard yard and the standard pound are kept in the Department of Inland Revenue at Ottawa.

From the yard and the pound other convenient units are derived. For example, we know that

12 inches (in.) = 1 foot
3 feet (ft.) = 1 yard
1760 yards (yd.) = 1 mile

and that

16 ounces (oz.) = 1 pound
2000 pounds (lb.) = 1 ton

Thus the height of a 6-foot boy could be expressed as 72 inches, or 2 yards, or 0.0013 mile. Similarly, the weight of a 150-pound boy could be expressed as 2400 ounces, or 0.075 ton. There is, however, a unit that best suits the particular situation, and so we say the boy is 6 feet tall and weighs 150 pounds.

The Metric System

In 1790, the French established the metric system with much simpler relationships between the various units than is the case in the British system. The metric system is a ***tens*** system. The basic unit of length is the meter, and the basic unit of mass (or weight) is the kilogram. Other units are obtained by increasing or decreasing the basic unit ten times; that is, by moving the decimal point to the right or left. Because of its simplicity, the metric system has been adopted by scientists everywhere. It is used even for general purposes in all countries except the British Commonwealth of Nations and the United States. Thus, in all European countries except England, the weight of an automobile is expressed in kilograms (rather than pounds) and its speed is expressed in kilometers per hour (rather than miles per hour).

The table of lengths is

10 millimeters (mm.) = 1 centimeter
10 centimeters (cm.) = 1 decimeter
10 decimeters (dm.) = 1 meter
10 meters (m.) = 1 dekameter
10 dekameters = 1 hectometer
10 hectometers = 1 kilometer (km.)

The most common prefixes are ***milli-***, ***centi-***, and ***kilo-***, and they mean respectively one-thousandth of, one-hundredth of, and one thousand times the standard of weight or length. Thus,

1 m. = 1000 mm.
1 m. = 100 cm.
1000 m. = 1 km.

A millimeter is a very small length, about equal to the thickness of the wire of a paper clip. A centimeter is a little less than half an inch, and a meter is a little longer than a yard (see Fig. 2-5).

If we measure the length of the word ***decimal*** with a ruler, we find it to be about 1.2 cm. This can be converted to millimeters by moving the decimal point one place to the right, and to meters by moving it two places to the left. Thus 1.2 cm. = 12 mm. = 0.012 m.

Similarly, a table of weights is

10 milligrams (mg.) = 1 centigram
10 centigrams (cg.) = 1 decigram
10 decigrams (dg.) = 1 gram
10 grams (gm.) = 1 dekagram
10 dekagrams = 1 hectogram
10 hectograms = 1 kilogram (kg.)

It is convenient to remember a few useful corresponding lengths and weights in the British and metric systems.

1 in. = 2.54 cm.
1 m. = 39.37 in.
1 km. = 5/8 mile (approximately)
1 lb. = 454 gm.
1 kg. = 2.20 lb.

For example, a 150-pound boy weighs 150/2.2 kilograms, which is approximately 68 kg.

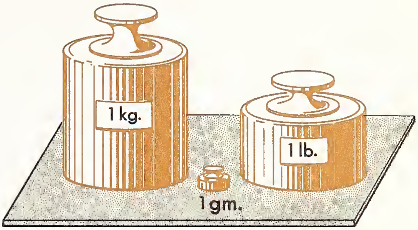

Fig. 2-6. The mass of a standard kilogram is 2.2 times the mass of a standard pound weight.

The international standard meter and kilogram are kept in the Bureau of Weights and Measures at Sèvres near Paris. Accurate copies of these standards are also kept in Ottawa.

Solving Problems in Weights and Measures

The solving of a few problems will give useful practice in using the tables of weights and measures.

Example 1. Express the sum of 340 centimeters, 8.6 meters and 0.123 kilometers in meters.

$$\begin{aligned} & 340 \text{ cm.} + 8.6 \text{ m.} + 0.123 \text{ km.} \\ = \; & 3.4 \text{ m.} + 8.6 \text{ m.} + 123 \text{ m.} \\ = \; & 135 \text{ m.} \end{aligned}$$

Example 2. A boy is 5 feet 10 inches tall. What is his height in centimeters?

$$\begin{aligned} \text{Height} &= 5 \text{ ft.} + 10 \text{ in.} &&= 70 \text{ in.} \\ &= 70 \times 2.54 \text{ cm.} &&= 178 \text{ cm.} \end{aligned}$$

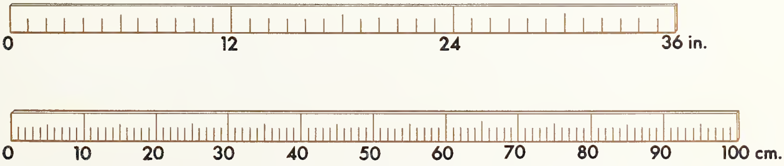

Fig. 2-5. A meter is a little longer than a yard.

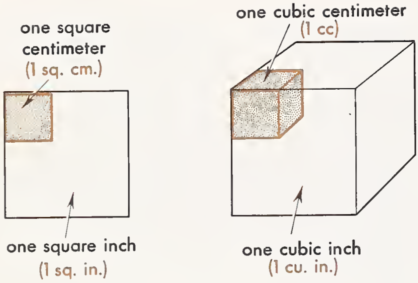

Fig. 2-7. Units of areas and volume.

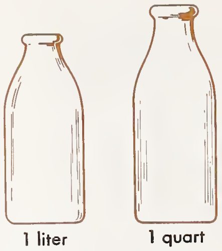

Fig. 2-8. One liter is approximately nine-tenths of a quart.

Example 3. Express the weight of 10 pounds of copper in (a) grams, (b) kilograms.

$$\begin{aligned}\text{Weight} &= 10 \text{ lb.}\\ &= 10 \times 454 \text{ gm.}\\ &= 4540 \text{ gm.}\\ &= 4.54 \text{ kg.}\end{aligned}$$

Area and Volume

It is often necessary to compute the area of a surface, or the volume of an object. A surface has two dimensions, length and width. For example, if the length of this page is 22 centimeters and the width is 15 centimeters, the area is the product of these values. Or,

$$\text{Area} = 22 \text{ cm.} \times 15 \text{ cm.} = 330 \text{ sq. cm.}$$

Notice that the units of area are expressed in square measure.

An object such as a box has three dimensions, length, width, and height, and the volume of the box can be found by multiplying these three dimensions. Thus if a box is 10 cm. long, 7 cm. wide, and 5 cm. high, its volume is 10 cm. × 7 cm. × 5 cm., or 350 cc. Notice that the symbol for cubic centimeters is cc.

Volume of Liquids

It is customary to measure the volume of liquids in quarts and gallons. A quart is a unit of capacity or liquid volume. An imperial gallon equals 1.2 American gallons. Similarly imperial quarts and pints are correspondingly larger than American quarts and pints. The unit corresponding to the quart in the metric system is called the *liter*. (1 liter = 0.88 quart = 1.76 pints. See Fig. 2-8.) A smaller unit is the milliliter (ml.) which, as the name suggests, is one-thousandth of a liter. The milliliter is almost identical with a cubic centimeter so that, for our purposes, we can regard them as similar units. We can say 1 liter = 1000 ml. = 1000 cc.

In the following chapters we shall make frequent references to length, volume, and weight; their units will be expressed both in the British and metric systems.

Things to Remember

The *mass* of a body is the quantity of matter in the body.

The *weight* of a body is a measure of the attraction of the earth upon the body.

In the *British system* the unit of length is the yard and the unit of mass is the pound; in the *metric* system the unit of length is the meter and the unit of mass is the *kilogram*.

Milli- means one-thousandth of; *centi-* means one-hundredth of; *kilo-* means one thousand times.

1 inch = 2.54 cm.
1 kg. = 2.2 lb.

Questions

1. How could you find the number of centimeters in an inch from a line you had drawn with a ruler?
2. Explain how a spring balance works.
3. Does a spring balance measure mass or weight? Explain.
4. If your normal weight is 150 pounds, would it be more or less than this amount if you were launched into space in a rocket? Explain.
5. Write what you know of the origin of the following units of length: [**a**] inch, [**b**] foot, [**c**] cubit, [**d**] yard.
6. Explain why it was necessary to have an imperial yard and an imperial pound.
7. What is the advantage of the metric system over the British system? Explain.
8. Name units of volume in the British and metric systems.

Problems

1. Airline passengers are allowed 40 pounds of baggage for travel in Canada, and 66 pounds for a trip to Europe. Express these weights in kilograms.
2. The length of a line is 10.16 centimeters. What is the length in [**a**] millimeters, [**b**] meters, [**c**] inches?
3. What is the length in feet of a building 100 meters long?
4. Express the weight of a 100-pound boy in [**a**] ounces, [**b**] kilograms, [**c**] milligrams?
5. Calculate the number of grams in an ounce.
6. A flask contains 5 liters of water. Express this volume in [**a**] milliliters, [**b**] quarts.
7. A cardboard box has the following dimensions: length, 3 inches; width, 4 inches; and height, 5 inches. Find the volume of the box in [**a**] cubic inches, [**b**] cubic centimeters, [**c**] cubic meters.
8. [**a**] How much smaller is an American gallon than an imperial gallon?
   [**b**] How much larger is an imperial quart than an American quart?

3

Force, Work, and Power

If we pull on a rope attached to a sled, we exert a force on the sled. How could this force be measured? In the last chapter we used a spring balance to measure weight. A spring balance can also be used to measure the force in a rope. For example, if we attach a spring balance to the rope as shown in Fig. 3-1A, the spring balance might read 50 pounds.

Various Kinds of Force

There are many kinds of forces besides *pull*. If the sled can be moved by a pull of 50 pounds it can also be moved by a *push* of 50 pounds. Another kind of force is *weight*. As stated in the last chapter, the weight of a body is the attractive force the earth exerts on the body. Force is also exerted by a metal as it expands, and by water as it freezes. Air can also exert a force. Wind blowing against the sails of a boat causes it to move at a good clip, and compressed air in the tires of an automobile exerts enough force to hold up the car.

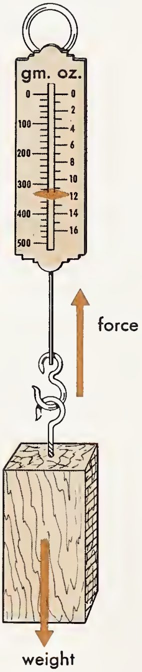

Fig. 3-1A. The spring-balance reading gives the weight of the block.

Experiment

3-1. To show that different amounts of force may be needed to move a body

Screw a hook into a rectangular block of wood. (A convenient weight is 600 to 800 grams.) Lift the block by a spring balance. How much force is needed to lift the block?

Now pull the block along the table top and observe that the reading of the spring balance is considerably less.

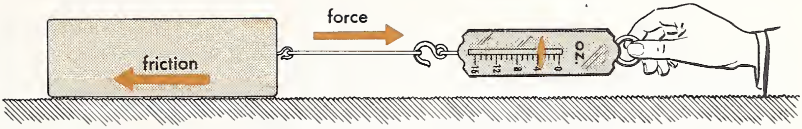

Fig. 3-1B. The spring-balance reading gives the force of friction.

How can we account for the different readings of the spring balance? In the first case we apply a force vertically up to counteract the downward pull of gravity on the block (see Fig. 3-1A). In the second case we apply a force to overcome friction between the block and the table, a force that is considerably less than the weight.

From these simple experiments we could say that ***a force is a push or pull that tends to set a body in motion.*** Of course, a force does not always make a body move. For example, when a body rests on the ground its weight does not set it in motion. Why not?

Friction

Let us now consider friction as a force that always opposes the motion of a moving body. Thus if the block rests on a table and is pulled to the right, the force of friction is exerted to the left (see Fig. 3-1B). If the block is pulled to the left, the direction of the force of friction is to the right (see Fig. 3-2). In both cases the force of friction opposes the applied force.

Suppose the force of friction between the surfaces is 2 pounds. If the applied force is less than 2 pounds, the block will not move. But if the applied force is just a little bit greater than 2 pounds, the block will move.

The force of friction depends on the nature of the surfaces in contact, as the following experiment shows.

Experiment

3-2. To show that friction depends upon the nature of the surfaces in contact

Turn the block on its side and attach a spring balance. Pull it along the table top and read the spring balance. Pour some furniture oil on the table top. Pull the block over the table top again and read the balance.

Now, place a rather rough board on the table. Pull the block along the board and read the spring balance. Finally, pour some oil on the board, pull the block along the board, and read the balance.

Examine the various balance readings. What conclusions can be drawn? It should be apparent that there is less friction between the block and a smooth surface than between the block and a rough surface. Moreover, oil reduces friction between surfaces; or, expressed another way, friction is reduced by lubrication.

Is Friction Bad or Good?

Because friction always opposes motion we are inclined to think it always works against us. Indeed, it always does whenever machinery is in motion. If friction in machinery were not reduced, it would wear away the metal surfaces so that the moving parts would soon need repairs. As you already know, heavy frictional losses are largely prevented by lubrication. In an automobile engine, oil is spread over the surface of the cylinder by piston rings, thereby reducing the wear on the cylinder walls. Ball bearings or roller bearings in

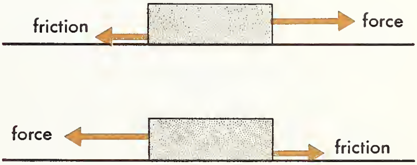

Fig. 3-2. Friction always opposes the applied force.

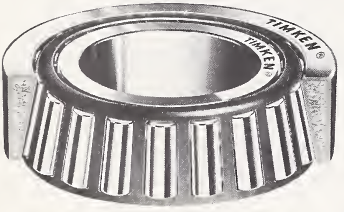

Fig. 3-3. A section of a bearing to show how steel rollers reduce friction between the moving parts.

the moving parts are also used to reduce friction. Powdered graphite is sometimes forced into creaky locks, and sticky drawers are rubbed with soap for the same purpose.

Let us now examine some of the useful effects of friction. We know it is much harder to walk on ice than on pavement. Why is this? There is little friction between our shoes and ice; if there were no friction between our shoes and the ice, we would be unable to move. Similarly, if there were no friction between the road and an automobile tire, the car would be unable to move. We may have seen a car stalled on smooth ice. When the engine runs, the rear wheels rotate rapidly but the car does not move forward. How could you get the car to move in such a situation?

If there were no friction, neither nails nor screws would "bite" on wood and they could not be used in the building of houses or other constructional work. You can undoubtedly think of many other ways in which friction serves a useful purpose, and you will rightly conclude that the advantages of friction far outweigh the disadvantages.

Work

So far we have concentrated our attention upon a force. But in most of the examples, a force is exerted through a distance, and distance is just as significant as force. We can emphasize this point by doing an experiment in which the same force is exerted through different distances.

Experiment

3-3. To exert a force through a distance

Lift a brick from the floor onto a chair. Now lift a brick from the floor onto a table. And, finally, lift the brick from the floor to the top of a stepladder.

Notice that in each case the force is the same. What is the force? The force is equal to the weight of the brick. But the force is exerted upward, whereas the weight is exerted downward. The distance the force is exerted is different in each case.

We would agree that more work is done in lifting the brick to the top of the step-

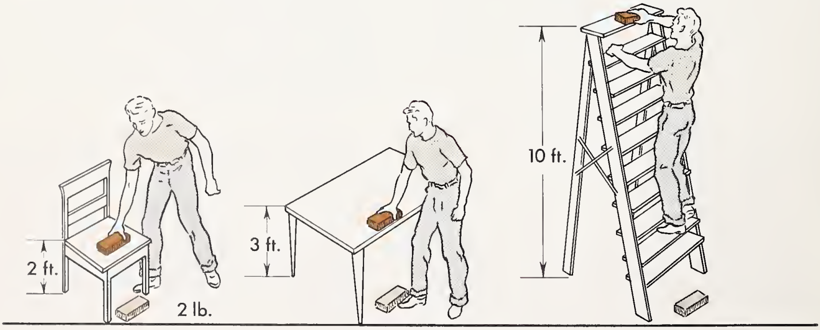
2 ft.
2 lb.
3 ft.
10 ft.

Fig. 3-4. A brick is lifted from the floor onto (1) a chair, (2) a table, and (3) a stepladder.

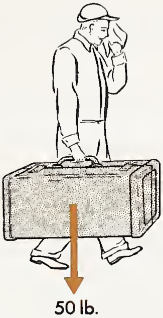

Fig. 3-5. No work is done as the suitcase is being carried.

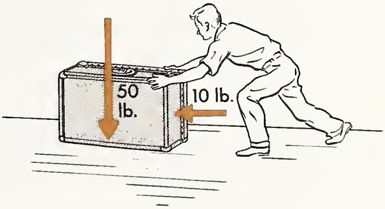

Fig. 3-6. Work is done as the suitcase is pushed along the platform.

ladder than in lifting it onto the chair. What, then, is *work*? Clearly both force and distance are involved in doing work and *we can define work as the application of a force through a distance*. This is an important definition. Let us see what it means by referring to Experiment 3-3.

Suppose that the force is 2 pounds, and that the distance from the floor to the chair is 2 feet. Then the amount of work we have done is the product of the force and the distance which is 2 feet times 2 pounds or, as we usually say, 4 foot-pounds. If the stepladder is 10 feet high, then 20 foot-pounds (10 feet × 2 pounds) of work are done in lifting the brick. We usually write 20 foot-pounds as 20 ft.lb. How much work is done in lifting the brick onto the table assuming the table is 3 feet high? The answer is clearly 6 foot-pounds.

The Meaning of the Term Distance

Notice that in lifting the brick, a force of 2 pounds is exerted *upward* and the direction of distance is also *upward*. That is to say, in measuring work *the direction of distance (or displacement) must be in the same direction as the applied force*. For example, suppose you carry a suitcase weighing 50 pounds a horizontal distance of 100 yards (see Fig. 3-5). Do you do any work? A little work is done in lifting the suitcase off the ground (if it is lifted six inches, the work done is 25 foot-pounds—why?), but no work is done while it is being carried 100 yards parallel to the ground. Why not? No force is being exerted along the direction of displacement (the directions of force and displacement are perpendicular to each other) and therefore no work is done on the suitcase.

Suppose, however, we drag (or push) the suitcase along the platform at a railroad station (see Fig. 3-6). Is work done in this case? This time we exert a force to overcome friction between the suitcase and the platform. Hence the applied force is in the direction of the displacement, and therefore work is done. If the force of friction is 10 pounds and the suitcase is pushed a distance of 10 yards, how much work is done? The answer is 300 foot-pounds.

The Meaning of the Term Work

In carrying the suitcase no work is done, though we may become tired. Hence the scientific use of the word "work" is restricted in its meaning since it implies (1) both force and displacement and (2) force and displacement must be in the same direction. Let us consider still another example to illustrate the difference between the "popular" and scientific meanings of work. Suppose we push on an automobile stuck in the mud. If we fail to move the automobile we do no work even though the effort makes us very tired. Why not?

The following additional examples illustrate the measurement of work in both the British and metric systems.

Example 1. A force of 30 pounds is needed to push a wheelbarrow loaded with a 100-pound sack of potatoes. How much work is done in moving the wheelbarrow 50 feet?

Work = force × displacement
= 30 lb. × 50 ft. = 1500 ft.lb.

Example 2. How much work is done when a match box is pushed a distance of 12 centimeters by a force of 25 grams?

Work = force × displacement
= 25 gm. × 12 cm.
= 300 gm.cm.

Notice that, in writing work units, it is customary for distance units to precede force units in the British system whereas force units precede distance units in the metric system.

Example 3. How much work is done if a weight of 30 kilograms is lifted vertically through 4 meters?

Work done = force × displacement
= 30 kg. × 4 m.
= 120 kg.m.

Work Input and Work Output

Support a smooth board, about a yard long, on a stand as shown in Fig. 3-7. This simple arrangement is a machine; it is an ***inclined plane***. We shall pull several objects up the inclined plane, the first being a "car" with wheels, a device that moves up the plane without much friction.

Experiment

3-4. To pull a load up an inclined plane

Load the car with a heavy weight such as a lead cylinder. Attach a spring balance to the car and pull it up the inclined plane

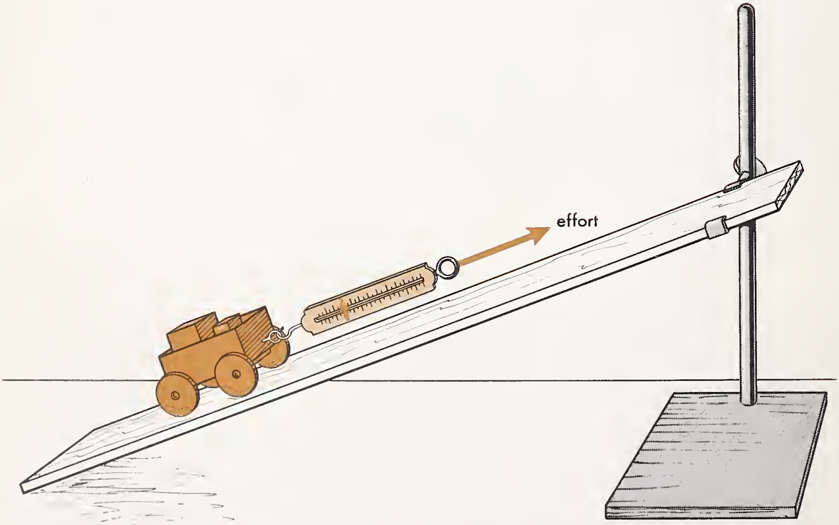

Fig. 3-7. A loaded car is pulled up a smooth board supported at one end on a stand.

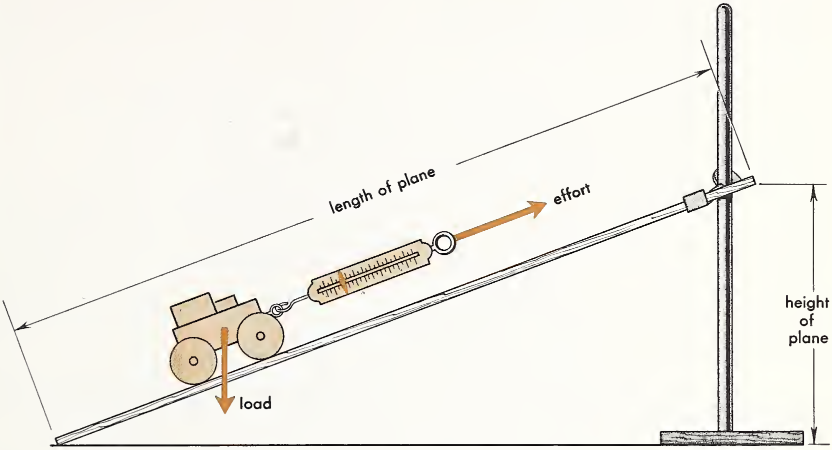

Fig. 3-8. An inclined plane.

(see Fig. 3-8). Read the spring balance in grams. Now weigh the car and the load either by the spring balance or an equal-arm balance. Measure the length of the plane and also the height of the plane in centimeters.

The force we exert in pulling the car up the plane is called the ***input force*** or the ***effort***. The effort was applied through a distance; that is, the effort did work on the machine. The work done by the effort is called ***input work***. Hence, we can say

input work = effort × distance through which the effort is applied.

If we assume the input force (or effort) is applied through the whole length of the plane, we can compute the input work in gram-centimeters.

The inclined plane exerts a force on the load, thereby lifting it vertically. The force exerted by the plane is called the ***output force***, or ***resistance***. Thus the inclined plane exerts a force on the load equal to its weight, and lifts the load through the height of the plane. The work done by the machine on the load is called the ***output work***. Or, we can say

output work = output force (or resistance) × the vertical distance through which the output force is exerted.

We can now compute the output work done by the inclined plane in lifting the load to the top of the plane. How does the output work compare with the input work? Your computation should show that the output work very nearly equals the input work. Why *very nearly?* Why does not output work equal input work exactly? Notice that the input force does two jobs; it pulls the load up the plane and it also overcomes friction between the wheels and the plane. The output force, on the other hand, merely lifts the load. ***If there were no friction we would find that the output work exactly equals the input work.*** This statement is sometimes called the ***law of machines***. If the length of the plane = d, and the height of the plane = h, then

work input = work output

E × d = R × h

The following example illustrates an application of the law of machines.

Example 4. Compute the force needed to pull a load of 900 grams up a smooth inclined plane, 150 centimeters long and 30 centimeters high.

$$E \times d = R \times h$$

$$\therefore E = \frac{R \times h}{d}$$

$$= \frac{900 \text{ gm.} \times 30 \text{ cm.}}{150 \text{ cm.}} = 180 \text{ gm.}$$

Mechanical Efficiency

In Experiment 3-4 we reduced friction to a minimum by using a smooth plane and freely rotating wheels on the car. We shall now compute input work and output work using a rougher board and a block of wood.

Experiment

3-5. To compute input and output work on an inclined plane

Support one end of a board, about 6 feet long, on a desk or table as shown in Fig. 3-9. Attach a spring balance to the wooden block used in Experiment 3-2 and pull the block up the slope of the board. Measure the input force in ounces. Also measure the height and length of the plane in inches. Now, assuming the block is moved from the bottom to the top of the plane, compute the input work and the output work in inch-ounces or foot-pounds. Which is the greater?

It is apparent that the work input is much greater than the work output. Why is this? In this case friction is a larger factor than in Experiment 3-4, and the work done in overcoming friction is considerable. Thus the law of the machine must be amended to read

work input = useful work output + work done against friction.

Thus suppose the weight of the block (R) is 12 oz. ($\frac{3}{4}$ lb.) and that the input force (E) is 8 oz. ($\frac{1}{2}$ lb.) Then the input work (E × d) is $\frac{1}{2}$ lb. × 6 ft. = 3 ft. lb., and the output work (R × h) = $\frac{3}{4}$ lb. × 3 ft. = $2\frac{1}{4}$ ft. lb. Therefore, $\frac{3}{4}$ ft. lb. ($3-2\frac{1}{4}$) of work is "wasted" in overcoming friction. ***The ratio of the useful work to the input work is called the efficiency of a machine.***

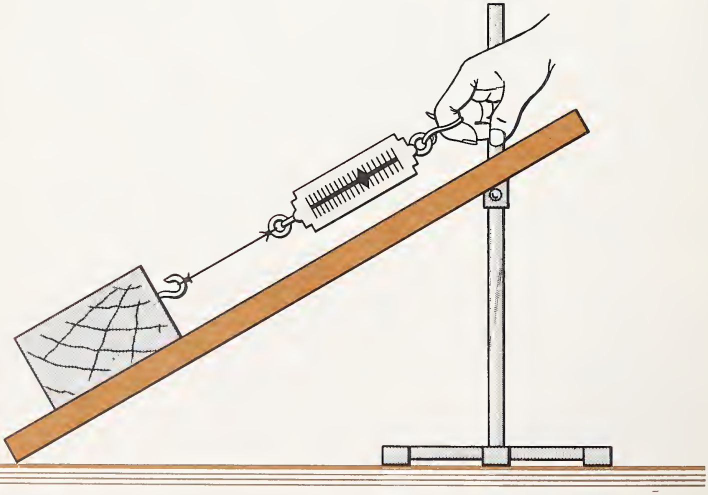

Fig. 3-9. A wooden block is pulled up an inclined plane.

The ratio is usually expressed as a percentage so that in the above example we can say

$$\begin{aligned}\text{efficiency} &= \frac{\text{output work}}{\text{input work}} \times 100 \\ &= \frac{2\frac{1}{4}\text{ ft. lb.}}{3\text{ ft. lb.}} \times 100 \\ &= \frac{9}{12} \times 100 = 75\text{ per cent}\end{aligned}$$

In every machine there is some friction. Therefore the useful work output is always less than the work input. As we shall read in the next chapter, there is a great deal of friction in a jackscrew and its efficiency is very low. On the other hand, there is little friction in a lever (in fact, some kinds of levers are almost frictionless), and its efficiency is very high.

In our computation following Experiment 3-5 we discovered that the work done against friction was $\frac{3}{4}$ foot-pound. Can you now compute the actual force of friction between the surfaces of the wood block and the inclined plane? If f represents the force of friction and d the length of the plane, then f × d represents the work done against friction. Hence

$$\begin{aligned}f \times d &= \tfrac{3}{4}\text{ ft. lb.} = 12\text{ ft. oz.} \\ \therefore f &= \frac{12\text{ ft. oz.}}{d} = \frac{12\text{ ft. oz.}}{6\text{ ft.}} = 2\text{ oz.}\end{aligned}$$

That is, the force of friction is 2 ounces or 1/8 pound.

Mechanical Advantage

You will recall that the input force applied to the block on the inclined plane was less than the output force (the weight of the block). Suppose a man wishes to haul a 300-pound crate onto a truck (see Fig. 3-10). No ordinary man can lift a 300-pound crate but he can do the job by using a plank as an inclined plane. Suppose he moves the crate by exerting a force of 50 pounds along the direction of the plane. The ratio $\frac{300\text{ lb.}}{50\text{ lb.}} = 6$ tells us the number of times the machine has increased the force that is applied to it. This is clearly an important thing to know about a machine. It is called *mechanical advantage*. Or, we can say

$$\text{mechanical advantage} = \frac{\text{output force}}{\text{input force}} = \frac{\text{resistance}}{\text{effort}}$$

Or, in symbols, $MA = \frac{R}{E}$

If the mechanical advantage of a machine is greater than 1, then clearly the output force is greater than the input force, and we say the machine multiplies the applied force. In some machines the mechanical advantage is less than 1. Such a machine reduces the applied force. It may seem strange that a useful machine should reduce the applied force. We shall consider at least one machine that reduces force in the next chapter.

The following example shows how the input force can be computed from the output force and the mechanical advantage.

Example 5. What force is needed to lift a weight of 24 pounds up an inclined plane whose mechanical advantage is 8?

$$MA = \frac{R}{E}$$

$$E = \frac{R}{MA} = \frac{24\text{ lb.}}{8} = 3\text{ lb.}$$

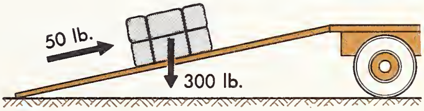

Fig. 3-10. The mechanical advantage of this inclined plane is 6.

To return to the example of pulling a load up a frictionless inclined plane, you will recall that

$$\begin{aligned} \text{work output} &= \text{work input} \\ \therefore \quad R \times h &= E \times d \\ \therefore \quad \frac{R}{E} &= \frac{d}{h} \end{aligned}$$

But $\frac{R}{E}$ equals mechanical advantage

Therefore, the ratio $\frac{\text{length of plane}}{\text{height of plane}}$ is also a measure of the mechanical advantage if the machine is frictionless. Indeed, for any machine with little friction it can be said that an approximate value of the mechanical advantage is given by the ratio $\frac{\text{effort distance}}{\text{resistance distance}}$, which is $\frac{d}{h}$.

Power

So far we have been concerned with the measurement of work. Sometimes, however, we wish to know how long a time is required to do this work; that is, we are interested in the *rate* at which work is done. Rate of work can easily be measured on an inclined plane.

Experiment

3-6. To measure rate of work on an inclined plane

Let us return to the plane used in Experiment 3-5. Mark two points on the plane, one near the top and another near the bottom, and measure the distance between the points. Now pull the block up the plane. Read the spring balance and measure the time in seconds for the front of the block to move from the lower to the upper point.

Now repeat the experiment moving the block at a faster rate, again noting the effort and the time. Compute the rate of work from each set of data.

Suppose that in one case the effort was 8 ounces ($\frac{1}{2}$ pound), the distance 5 feet, and the time 2 seconds. The rate at which work is done is

$$\begin{aligned} \frac{\text{force} \times \text{distance}}{\text{time}} &= \frac{\frac{1}{2}\text{ lb.} \times 5\text{ ft.}}{2\text{ sec.}} \\ &= 1.25\text{ ft. lb. per sec.} \\ \text{or } & 1.25\text{ ft. lb./sec.} \end{aligned}$$

The rate at which work is done is called power. Or,

$$\text{power} = \frac{\text{work}}{\text{time}}$$

and in the above experiment the power exerted was 1.25 foot-pounds per second.

Let us go back to the crate problem on page 25. Suppose that the length of the plank is 12 feet and that the force is 50 pounds and the time 20 seconds.

$$\begin{aligned} \text{Power input} &= \frac{\text{work input}}{\text{time}} \\ &= \frac{50\text{ lb.} \times 12\text{ ft.}}{20\text{ sec.}} \\ &= 30\text{ ft. lb. per sec.} \end{aligned}$$

If the time is shortened, greater power is needed to do the same amount of work.

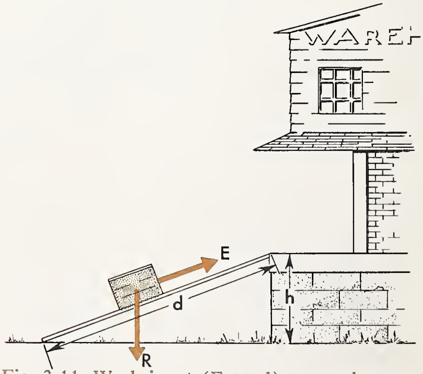

Fig. 3-11. Work input (E × d) = work output (R × h).

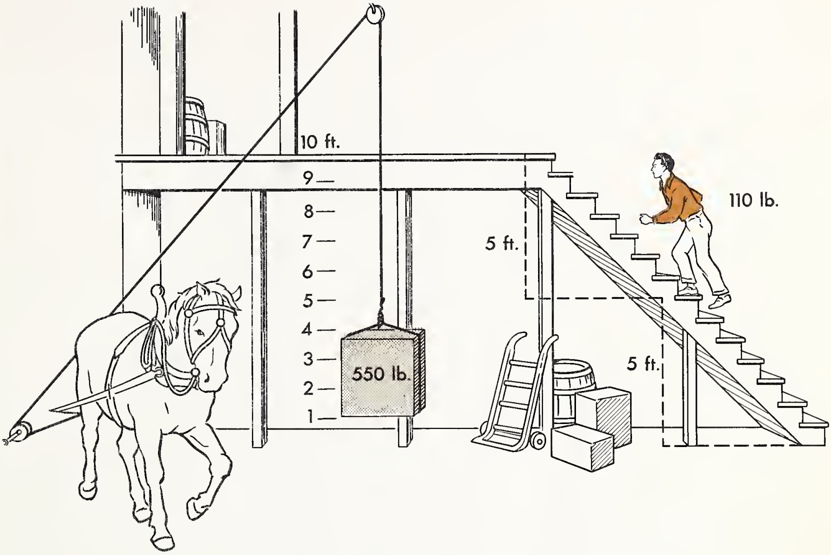

Fig. 3-12. How horsepower can be measured. The power required to lift the 550-pound load 1 foot in 1 second is 1 horsepower. If the boy reaches the top of the stairway in 10 seconds, he is using 1/5 horsepower.

Thus, if the crate is pulled up the incline in 15 seconds, the power is $\dfrac{50 \text{ lb.} \times 12 \text{ ft.}}{15 \text{ sec.}}$ or 40 ft. lb. per sec.

Another way of expressing it is in terms of ***horsepower***. This unit was first used by James Watt, the inventor of the steam engine, who wished to express the power of his engine in terms of the power developed by a horse. He found that a good horse could work at an average rate of 550 foot-pounds per second (or 33,000 foot-pounds per minute). This rate of doing work he called *1 horsepower* (h.p.). As you probably know, the engine of an automobile can develop more than 200 horsepower, and the engine of an airplane more than 2000 horsepower. A man can work at a steady rate of about 1/7 horsepower but, for short intervals, he can develop a much higher horsepower than this. Some boys (as described in ***Things to Do*** at the end of this chapter) can work at the rate of almost 1 horsepower if they make a great effort for a few seconds.

It should now be apparent that horsepower can be computed by dividing the rate of work done per second by 550. Thus the horsepower needed to pull the crate up the board (as described on page 25) is

$$\text{power} = \frac{50 \text{ ft. lb. per sec.}}{550 \text{ ft. lb. per sec.}} = \frac{1}{11} \text{ h.p. (or 0.091 h.p.)}$$

Things to Remember

A *force* is a push or pull applied to a body.

Friction is a force that always opposes motion.

Work is the product of a force and the distance moved in the direction of the force.

In any machine, *input work* equals output work plus the work done in overcoming friction.

The *efficiency* of a machine is the ratio of the useful output work to the input work.

Mechanical advantage is the ratio of the output force to the input force.

Power is the rate at which work is done.

One *horsepower* is a rate of 550 foot-pounds of work per second.

Questions

Part A

1. Define the term *force*. What are common units of force?
2. Define the term *work*. What are common units of work?
3. Define the term *power*. What are common units of power?
4. Define the term *efficiency*. Why are there no units of efficiency?
5. Define the term *mechanical advantage*. Does a mechanical advantage of 1 represent a gain in force? Explain.
6. "The weight of a body is a force." Explain what this statement means.
7. What is wrong with the following statement? The law of machines states: Input work equals output work plus the force of friction.
8. What is the meaning of the terms *effort* and *resistance*?

Part B

9. [**a**] What is friction?
   [**b**] Describe two examples of friction, one beneficial and the other disadvantageous.
10. A car stalled on an icy road rotates its wheels rapidly when the engine is running. Briefly describe two ways of getting the car started.
11. One boy says that no work is done if a sack of potatoes is moved from one position on the floor of a cellar to another. Another boy says work *is* done. Which is right? Why?
12. Why is an inclined plane called a machine?
13. "What is gained in force is lost in distance." This statement is often applied to a machine. What does it mean when applied to an inclined plane?
14. Explain why the ratio of the length to the height of a frictionless inclined plane is a measure of its mechanical advantage.
15. "Input power equals output power plus power used to overcome friction." Are you justified in making this statement concerning an inclined plane? Give reasons for your opinion.
16. Can a 2-horsepower engine lift as heavy a load as a 5-horsepower engine? Explain.

Problems

1. How much work is done by a 150-pound boy in climbing a flight of stairs 20 feet high?
2. One machine does 10,000 foot-pounds of work in 10 seconds, another does 60,000 foot-pounds in 2 minutes. Calculate the horsepower in each case.
3. In loading a truck with 10 bags of cement, 4500 foot-pounds of work are done. Compute the weight of each bag of cement assuming the floor of the truck is 3 feet above the ground.
4. A force of 120 grams is applied to a book supported on a table until 36,000 gram-centimeters of work are done. [**a**] Compute the distance in meters the book is moved. [**b**] What is the direction of the distance?
5. [**a**] Compute the force needed to pull a load of 20 pounds up a frictionless inclined plane, 5 feet long and 3 feet high.
   [**b**] What is the mechanical advantage?
   [**c**] What is the ratio of the length to the height of the plane?
   [**d**] What is the efficiency of the plane?
6. An effort of 60 pounds is needed to push a 200-pound bag of cement up an inclined plane 25 feet long and 5 feet high. Compute [**a**] the mechanical advantage, [**b**] the efficiency of the inclined plane, [**c**] the work done against friction, [**d**] the force of friction.
7. If the bag in Question 6 was pulled up the inclined plane in 4 seconds, what was [**a**] the input power (in foot-pounds per second), [**b**] the output power, [**c**] the input horsepower, [**d**] the output horsepower, [**e**] the power loss due to friction?

Things to Do

What is Your Horsepower?

The horsepower you are capable of developing can be approximately found by measuring the time it takes you to run up the stairs in the stairwell of a building. First measure the vertical height from the floor to the top step of the stairwell. This should not be less than 20 feet. At a given signal, run up the stairs as rapidly as possible, the time being recorded to the nearest half-second. Several boys should enter the contest, the time of each being recorded.

On returning to the classroom each competitor can compute his own horsepower on the blackboard. All he needs is (1) his weight in pounds, (2) the vertical height of the stairs in feet, and (3) the time in seconds. For example, if a boy weighing 120 pounds runs up a flight of stairs 40 feet high in 11 seconds, his horsepower is

$$\frac{120 \times 40}{11 \times 550} = 0.79$$

To Reduce Friction by Rollers

Place a heavy box on a bench or table. Attach a spring balance to the box and find the force needed to move it. Now, rest the box upon some round pencils which act as roller bearings. Find the force needed to move the box on its roller bearings. Compare the two forces. What is your conclusion?

4

Machines

Machines are devices that help to do work. Their development has, through the ages, been associated with the advance of civilization, in contributing to the comfort of mankind. Today man has learned to combine several simple machines into more complex ones. Moreover, very little muscular effort is needed to operate even the most complex machinery. A diesel locomotive does a great deal of work; yet we know that the operator himself does practically no work at all.

But it was not always so. Man began to think about this problem when, tens of thousands of years ago, he first tamed animals and trained them to work for him. Even today, horses, oxen, elephants, and water buffalo serve the same purpose; they are beasts of burden.

Man made a still greater advance when he invented simple machines. By means of these he could exert forces greater than the muscular effort of men or animals. Buildings and monuments constructed in these early times show great understanding of the use of simple machines. An outstanding example of massive construction is the Great Pyramid near Cairo, Egypt, built almost 5000 years ago. Like all the Egyptian pyramids, it was a tomb, the resting place for the preserved body of a king.

The Great Pyramid is 480 feet tall and is built of more than two million blocks of limestone, each weighing more than 2 tons. Its construction was a colossal engineering feat. How was the Pyramid erected? It is believed that an inclined plane made of earth was used, and that the enormous blocks of rock were hauled up the incline on sledges and put into place (see Fig. 4-1). As the Pyramid grew in height, more earth was brought in to lengthen the plane. And, finally, when the construction was finished, all the earth had to be carried away to uncover the Pyramid. An early

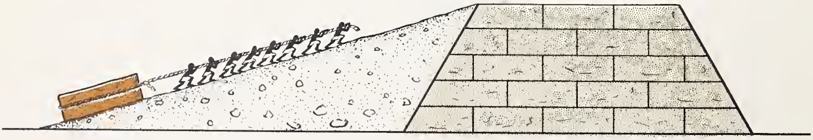

Fig. 4-1. In building the Pyramids it is thought that slaves dragged enormous blocks of rock up an incline constructed of earth.

historian tells us that 100,000 slaves worked for twenty years on this monumental job.

How were the massive pieces of rock lifted onto the sledges? Another kind of machine was needed for this purpose. This could have been a lever, or a pulley, or both. Early man learned that even the projecting branch of a tree could be used to help in lifting heavy objects. He simply threw a rope over the branch, fastened one end of the rope to the object, and pulled on the other end (see Fig. 4-2). This was the first crude pulley. There was a good deal of friction between the branch and the rope. So the next step was to reduce friction by making a pulley wheel that would rotate and by grooving the rim of the wheel to take a rope. There is evidence to show that pulleys have been used for thousands of years.

Pulleys

In spite of their great age pulleys are very much in use today. You have probably noticed the pulleys on cranes used to lift the heavy steel supports needed in constructional work. Even in the home pulleys are needed. For example, the sash rope which connects a window to a counterweight passes over a pulley in the window frame. Pulleys are also useful on a farm as shown in Fig. 4-3. Here a pulley enables a farmer to lift a bale of hay into the loft of his barn. How does a pulley operate? First, we shall consider the simplest kind of pulley, a single fixed pulley.

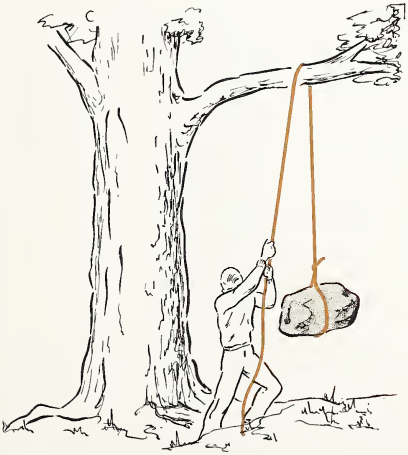

Fig. 4-2. The earliest pulley was probably a rope thrown over a branch of a tree.

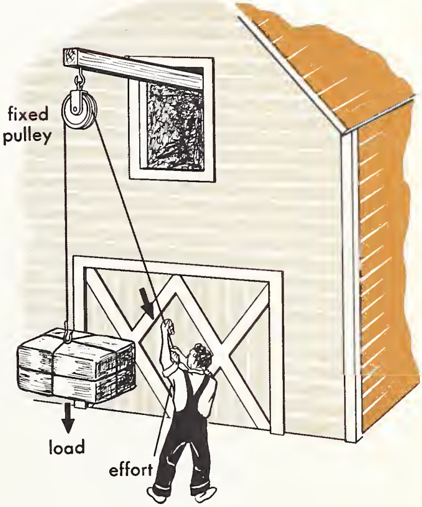

Fig. 4-3. A fixed pulley enables the farmer to lift hay into the loft.

A Single Fixed Pulley

The arrangement shown in Fig. 4-3 is a single fixed pulley. The pulley inside a window frame is also a single fixed pulley. Let us set up such a pulley and discover its mechanical advantage and efficiency and, in general, its usefulness as a machine.

Experiment

4-1. A single fixed pulley as a machine

Attach a steel rod to two large ring stands by means of clamps as shown in Fig. 4-5. Suspend a pulley from the rod and pass a

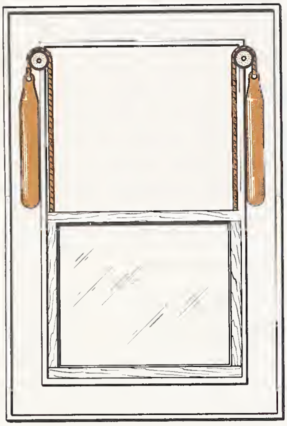

Fig. 4-4. The fixed pulleys change the downward direction of the weights to an upward pull on the window.

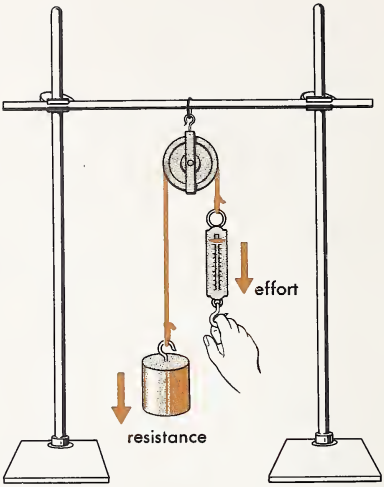

Fig. 4-5. In a single fixed pulley the effort equals the resistance.

strong thread or a piece of fish line over the pulley. Tie a load (for example, a 1-kilogram weight) to one end of the thread and attach the hook of a spring balance to the other end. Pull down on the spring balance until the load (the resistance) rises. Read the spring balance. This is the effort. Also measure the distance the effort moves down (d_E) and the distance the resistance moves up (d_R). Compute the work input and the work output.

First we notice that the balance reading (the effort) is about the same as the load (the resistance). Actually the effort is a little greater than the resistance. Why? Some of the effort is used to overcome the force of friction. If there were no friction, the effort and resistance would be equal and opposite forces. Hence we can say that the mechanical advantage of the pulley (R/E) equals 1. Then again, we find that the effort distance is the same as the resistance distance; the effort moves down just as far as the resistance moves up. Here, then, is a machine that gives neither a *gain* in force nor a *loss* in distance. Then what is the value of the fixed pulley as a machine? It changes the direction of the effort; it enables us to pull a load upward by exerting an effort downward. This is often a convenient thing to do, as it enables us to use our own weight as the effort.

Finally, observe that the efficiency is very high. But this is what we would expect. Why?

A Single Movable Pulley

Suppose we rearrange the fixed pulley so that it becomes movable as shown in Fig. 4-6. Will this affect its mechanical advantage or, in general, will it affect its usefulness as a machine? Let us find out.

Experiment

4-2. A single movable pulley as a machine

Tie one end of a strong thread to the rod, support a pulley and load (R) on the thread, and attach the hook of a spring balance to the other end. The arrangement is shown in Fig. 4-6.

Move the spring balance upward and notice that the pulley and load also move upward. Read the spring balance (E) and compare this reading with the load (R).

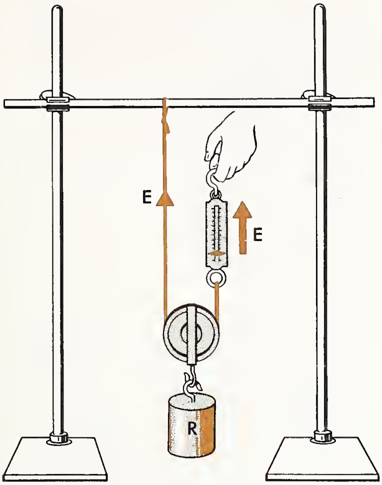

Fig. 4-6. In a single movable pulley the effort is approximately half the load.

Now measure the distance your hand rises in moving the balance and also the distance the load rises.

What conclusions can be drawn from our data? First, comparing the effort (E) and load (R), we find that E is approximately one-half of R; if R equals 1000 grams, E is about 500 grams. Actually, it is a little more than 500 grams. Why? Again some of the effort E is used to overcome friction. If there were no friction, the effort would be exactly one-half of the load. Hence the mechanical advantage (R/E) of this machine is 2. How can we account for it? The load is supported by two sections of the thread, one attached to the fixed rod and the other attached to the spring balance. The load is equally divided between the support and the spring balance, and, therefore, the upward pull exerted on the spring balance is equivalent to one-half of the resistance. Since the effort is less than the resistance, the machine is said to give a *gain in force*.

Let us now examine the distances through which the effort and resistance move. We find that the effort distance (d_E) is twice the resistance distance (d_R). Or, expressed another way, the load rises only one-half the distance through which the hand moves. This is sometimes called a *loss in distance*. In other words, we can say, *What is gained in force is lost in distance.*

And, finally, what of the speeds of the effort and the resistance? When the spring balance (or hand) moves, the load also moves. Moreover, effort and resistance move for the same length of time. Therefore, the speed at which the load moves is only one-half of the speed at which the hand (or effort) rises. Or, expressed another way, we can say, *What a machine gains in force it loses in speed.*

Applying the law of machines to a single movable pulley (and neglecting friction) we again conclude

$$\begin{aligned} \text{work input} &= \text{work output} \\ E \times d_E &= R \times d_R \end{aligned}$$

and that

$$\text{mechanical advantage (MA)} = \frac{R}{E} = \frac{d_E}{d_R} = 2$$

A Combination of a Fixed and Movable Pulley

We can combine the fixed and movable pulley and thereby obtain the advantages of both. This arrangement is shown in Fig. 4-7.

Experiment

4-3. A combined fixed and movable pulley

Attach a fixed pulley to the supporting rod. Fasten one end of a thread to this pulley, support a movable pulley and load on the thread, and pass the other end of the thread over the fixed pulley. Attach this end of the thread to a spring balance (see Fig. 4-7). Pull down on the spring balance and take its reading as the load (R) rises. Compare the distance the effort moves down with the distance the load moves up.

The data show that the effort (E) is one-half of the load (R). Moreover, in this combination, the effort is conveniently exerted downward. It is now apparent that the farmer can improve his hauling system shown in Fig. 4-3 by attaching one end of the rope to another hook in the beam, placing a movable pulley on the rope between the hook and the fixed pulley, and attaching the bale of hay to the movable pulley block. The new arrangement is shown in Fig. 4-8.

If the bale of hay weighs 200 pounds, we now know the pull exerted by the farmer would be about 100 pounds. But suppose he wished to reduce the applied force to 50 pounds. How could he do it? If the number of supporting ropes is increased, the applied force is correspondingly reduced. If there are 3 supporting ropes, the mechanical advantage is 3; if there are 4 supporting ropes, the mechanical advantage is 4, and so on. The simplest way of increasing the number of supporting ropes is to add more movable pulleys to support the load, and more fixed pulleys to the beam. Such a pulley system is called a ***block and tackle***; it is shown in Fig. 4-9. A combination of fixed and movable pulleys (the equivalent of a block and tackle) is used in the following experiment.

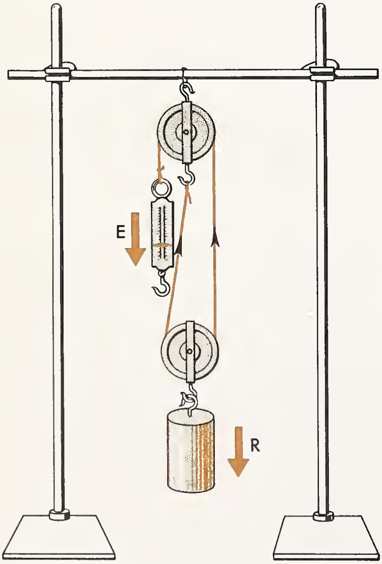

Fig. 4-7. A combined fixed and movable pulley.

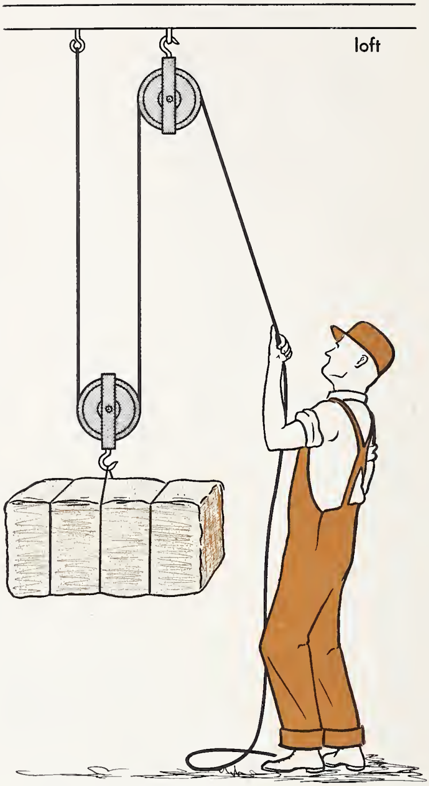

Fig. 4-8. If the bale of hay weighs 200 pounds, the pull on the rope is about 100 pounds.

Experiment

4-4. A pulley system

Using the rod as support, arrange a pulley system similar to that shown in Fig. 4-9, which consists of 2 movable and 2 fixed pulleys. Raise the load through a distance of 6 inches. How far does the effort move?

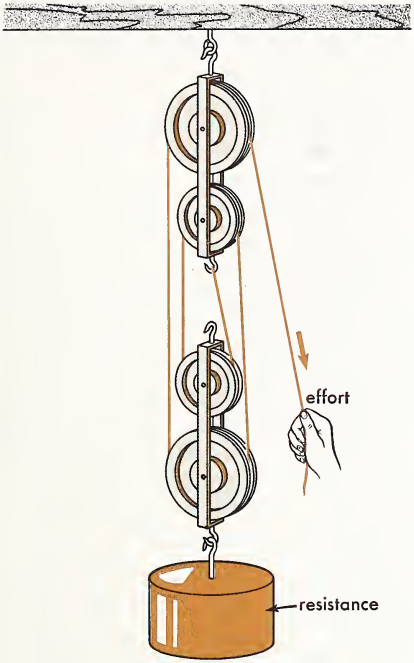

Fig. 4-9. A combination of fixed and movable pulleys.

What is the effort and the load? Compute the mechanical advantage from the effort (the applied force) and the resistance (the load). Does this value agree with the number of supporting strings? What is the efficiency of this machine? Do your data verify the statements: (1) What is gained in force is lost in distance and (2) What is gained in force is lost in speed? How could you arrange this system of 2 fixed and 2 movable pulleys to give a mechanical advantage of 4? What advantage would be gained by arranging the pulleys to give an MA of 4 instead of 5?

It is now apparent that a block and tackle with a larger number of movable pulleys would give a still larger gain in force; that is, the greater the number of movable pulleys the less is the applied force. You may have seen a garage mechanic lift a heavy automobile engine from its seat by means of a pulley system called a differential pulley. He attaches the movable block to the engine and pulls on a chain that passes over the pulleys of the fixed block. And, as you probably observed, the engine is lifted by applying a surprisingly small force.

A Wheel and Axle

Another way to combine pulleys is to fix two pulleys of different sizes onto the same shaft so that they turn together. Such an arrangement is shown in Fig. 4-10. In this machine the larger pulley is usually called the ***wheel***, the smaller pulley is called the ***axle***, and the machine itself is called a ***wheel and axle***. If an effort is applied to a rope on the wheel, the wheel and axle rotate and a load, attached to a rope on the axle, is thereby raised. What is the particular advantage of the wheel and axle as a machine? To help us answer this

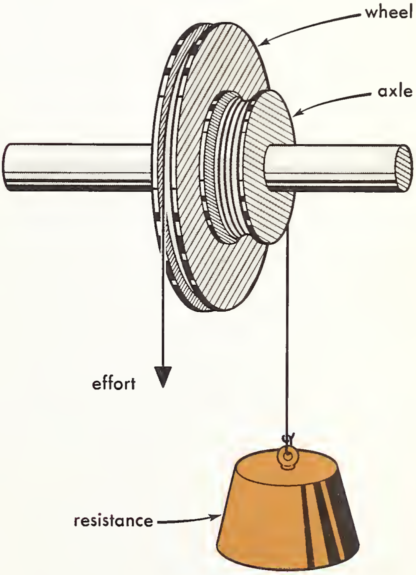

Fig. 4-10. A wheel-and-axle consists of two pulleys on the same shaft.

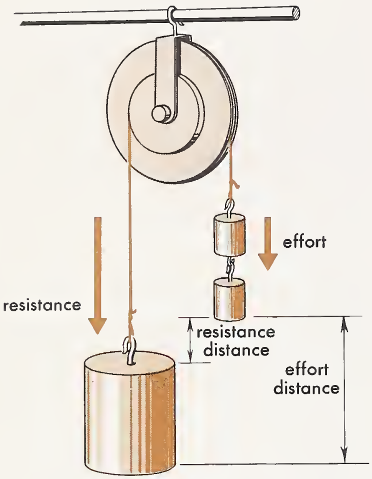

Fig. 4-11. In a wheel and axle the effort distance is greater than the resistance distance.

question let us set up a wheel and axle and operate it.

Experiment

4-5. A wheel and axle

Measure the circumference of the large and small wheels of a wheel and axle, and then support the machine on a rod as shown in Fig. 4-11. Attach a strong thread to the small wheel (the axle) and wind the thread around the axle five or six times in a counterclockwise direction. Attach some thread to the large wheel and wind the thread around the wheel two or three times in a clockwise direction.

Fasten a kilogram weight (the resistance) to the free end of the axle thread. Make a loop in the free end of the other thread and then attach weights to it, one at a time, until the resistance slowly rises. The sum of these weights is the effort. Measure the distances through which both effort and resistance move. What is the mechanical advantage of this machine? What is its efficiency?

From our data it is apparent that the load is greater than the applied force. In other words the machine multiplies force (or gains force), but, like an inclined plane or a block and tackle, it does so at the expense of both distance and speed. The load moves through a smaller distance and at a lower speed than the effort.

What would be the effect of interchanging the positions of the effort and resistance, applying the effort to the axle and attaching the load of 1 kilogram to the wheel? If we test this experimentally, we find that the applied force is now greater than the load, but that the load moves through a greater distance than the effort. Here, then, is a machine with a mechanical advantage of less than 1, a machine that gives a loss in force but a corresponding gain in distance and speed.

Various Kinds of Wheels and Axles

Applications of the wheel and axle are very common. A doorknob, the steering wheel of an automobile, a screwdriver, a water faucet, a spanner used to tighten a

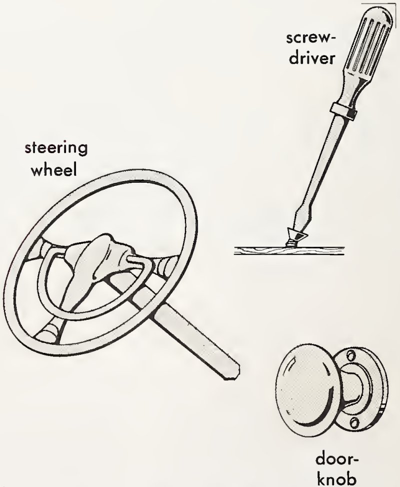

Fig. 4-12. A doorknob, the steering wheel of an automobile, and a screwdriver are examples of a wheel and axle.

bolt, are adaptations of the wheel and axle. In all these cases the wheel rotates with the axle, and there is a gain in force and a loss in distance. Thus a force is applied by the hand to the rim of a doorknob. This, in turn, rotates the axle which is connected with the latch of a lock. The force exerted on the latch is considerably greater than the force exerted by the hand. Why?

A bicycle pedal is another example of a wheel and axle (see Fig. 4-13). The force transmitted by the foot is increased when passed on from the pedal to the sprocket. Why? The force is then transmitted from front sprocket to the sprocket of the rear wheel by means of a connecting chain. The connecting of the sprockets by a chain is another adaptation of a wheel axle. Does this give a gain or loss in force? Why?

The Mechanical Advantage of a Frictionless Wheel and Axle

Let us now compute the mechanical advantage of a wheel and axle by considering the situation as shown in Fig. 4-14. If an effort, E, is applied to the wheel, both wheel and axle make a complete turn in the same time. How much work is done in one complete turn? You will recall that work is measured by the product of the force and distance. What is the distance covered in one complete turn of the wheel? Clearly, the circumference (C) of the wheel. But the circumference of the wheel is π times the diameter (D) of the wheel ($C = \pi D$). Similarly, the circumference (c) of the axle is π times the diameter (d) of the axle ($c = \pi d$). Hence we can say that in one complete turn

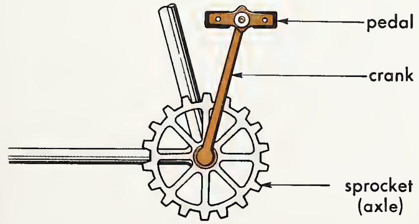

Fig. 4-13. A bicycle pedal is an example of a wheel and axle.

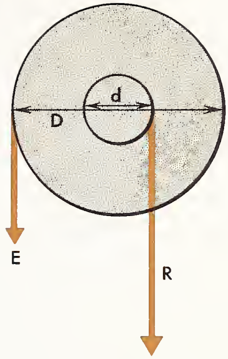

Fig. 4-14. The mechanical advantage of a wheel and axle is the diameter of the wheel divided by the diameter of the axle.

$$\text{input work} = E \times \pi D$$
$$\text{output work} = R \times \pi d$$
$$\text{hence } E \times \pi D = R \times \pi d$$
$$\text{and } \frac{R}{E} = \frac{\pi D}{\pi d}$$

Therefore, mechanical advantage =

$$\frac{R}{E} = \frac{D}{d} = \frac{\text{diameter of wheel}}{\text{diameter of axle}}$$

Again it should be stressed that this relationship (the mechanical advantage is equal to the ratio of the diameters) is only true for a frictionless machine. This we can call the theoretical mechanical advantage. Let us now return to the data in Experiment 4-5. How does the true mechanical advantage (computed from the forces) compare with the theoretical mechanical advantage (computed from the diameters or circumferences)? How do you account for the difference between these values?

The Screw

The screw is another common machine. It is invaluable in constructional work. As you know, it is used to bind together two pieces of board or to support a door by

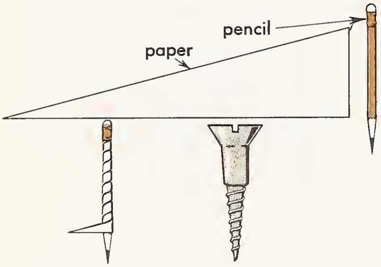

Fig. 4-15. A screw is a spiral inclined plane.

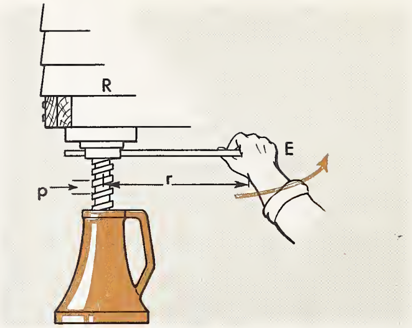

Fig. 4-16. A jackscrew.

its hinges. But there are many other kinds of screws besides those used in constructional work. The lid of a fruit jar is a screw and so is the base of a light bulb. With a corkscrew we can remove a tightly fitting cork from a bottle and with a jackscrew we can lift an automobile, or even a house. It is apparent that a screw enables us to overcome a large resistance by the application of a relatively small force. What is the principle of this machine we call a screw? Strange as it may seem, a screw is an inclined plane and the force we apply to turn a screw is the effort exerted up an inclined plane. Let us see why.

Experiment

4-6. To show that a screw is a spiral inclined plane

Cut a right-angle triangle out of a sheet of paper, making the base 6 inches and the height 2 inches. Now cut a second triangle making the base 6 inches and the height 3 inches. Roll one of the paper triangles tightly around a pencil (see Fig. 4-15) and hold the paper in place by Scotch tape. Now do the same with the other triangle on another pencil. It is apparent that the paper inclined plane has been rolled into a screw. Or we can say, that the threads of a screw form a spiral inclined plane. Thus the force applied to the screw is exerted through the whole length of the plane.

We know that as force is applied to an ordinary screw it bores into wood. Moreover, for one complete rotation, the screw bores into the wood a distance equal to the *pitch* of the screw (the pitch is the distance between two adjacent threads.) Notice that the pitch is quite different in the two paper screws you have made. In which of the two screws would the greater effort have to be made? Which would have the greater mechanical advantage?

A Jackscrew

A jackscrew (or jack, as it is usually called) is a screw designed to give a very large mechanical advantage—so large that an automobile can be raised by the application of a relatively small force. The jackscrew is supported on a metal base (see Fig. 4-16), and the thread of the screw fits into a spiral groove cut into the base. The screw is turned by applying a force to the handle (of length r).

Let us consider the input work and the output work for one complete rotation of the handle. The end of the handle moves through a circle of radius r. Hence

$$\begin{aligned}\text{input work} &= \text{force applied} \times \text{circumference of circle}\\ &= E \times 2\pi r\\ \text{output work} &= \text{load lifted} \times \text{pitch of screw (p)}\\ &= R \times p\end{aligned}$$

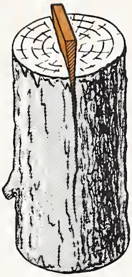

Fig. 4-17. A wedge.

Thus, by the principle of machines,

$$\text{input work} = \text{output work}$$
$$\therefore E \times 2\pi r = R \times p$$

Suppose that the handle is 3 feet (36 inches) long, that the pitch of the screw is $\frac{1}{4}$ inch, and that the force applied at the end of the handle is 50 pounds. What force is exerted by the machine? Or, in other words, how much load can be lifted?

$$\begin{aligned} R &= \frac{E \times 2\pi r}{p} \\ &= \frac{50 \times 2 \times 22/7 \times 36}{1/4} \\ &= 45{,}000 \text{ pounds} \end{aligned}$$

The mechanical advantage computed in this way is therefore

$$\frac{R}{E} = \frac{45{,}000 \text{ pounds}}{50 \text{ pounds}} = 900$$

This is a fantastically large mechanical advantage and it should now be apparent why so little effort is needed to lift an automobile with a jackscrew. We must remember, however, that there is a great deal of friction in a jackscrew, and in all screws for that matter. Indeed, because of friction, the actual mechanical advantage would be less than half the above value. But, although friction increases the force that is applied, it serves a useful purpose. If there were no friction between the screw and the base, the screw would unwind (that is, turn backward) as soon as the effort ceased to be applied.

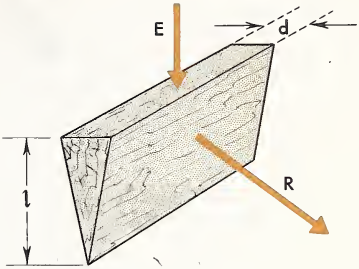

Fig. 4-18. A wedge is made up of two inclined planes, base to base.

A Wedge

Still another kind of machine is a wedge. A knife blade, a chisel, and a hatchet are examples of this machine. But the wedge we usually think of is that commonly used to split wood.

We can consider a wedge as made up of two inclined planes placed base to base (see Fig. 4-18). By applying a force E, the long sides of the wedge move into the wood a distance of l and the wood is split by a short distance (d). The output force (R) is perpendicular to each of the inclined faces. It can be shown that the theoretical mechanical advantage is $\frac{l}{d}$.

Tremendous splitting forces can be developed from hammer blows on the end of the wedge. But as in the case of the screw, friction is very great, and the actual ratio of the input force to output force cannot easily be computed.

The Uses of Machines

We have now considered five basic simple machines—(1) an inclined plane, (2) a pulley, (3) a wheel and axle, (4) a screw, and (5) a wedge. Complicated devices such as a crane, an automobile, or an airplane, are really combinations of these simple machines. What are the fundamental

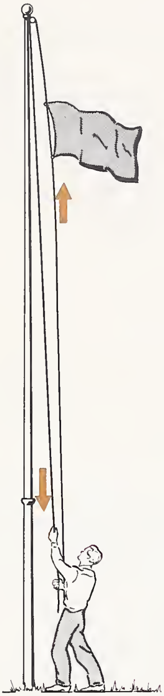

Fig. 4-19. The pulley on the flagpole changes the direction of the applied force.

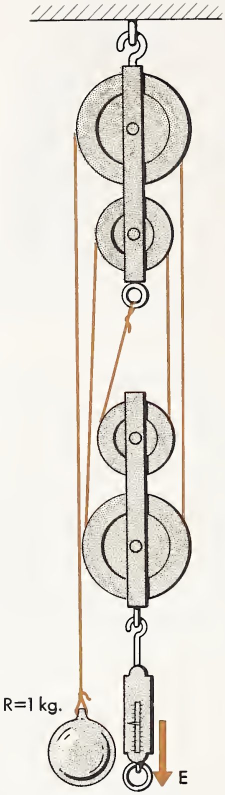

Fig. 4-20. A pulley system that gives a loss in force.

purposes of these machines? Our experiments show that machines may serve three useful purposes.

1. *A machine may increase the applied force.* This is probably the most common use of a machine. A man is unable to lift the rear end of an automobile unaided. However, a jackscrew will multiply the applied force thereby bringing this task within the scope of a man's effort. We must bear in mind, however, that a machine used to increase force always decreases speed. We know from experience that an automobile rises very slowly on a jackscrew, much more slowly than the hand moves in rotating the handle.
2. *A machine may change the direction of a force.* A pulley at the top of a flagpole makes it possible to raise a flag by pulling down on a rope. Without the pulley, the pole would have to be climbed to do the same task. That is, it is sometimes convenient to apply a force opposite in direction to the force needed to do a job.
3. *A machine may increase the speed of the applied force.* A bicycle enables us to travel faster than when we run, even though our leg movements are no faster in cycling than in running. This is because a much greater force is exerted on the pedals than is exerted by the back wheel on the ground. Again we see that if a machine is used to in-

crease speed, it always loses force.

To increase speed, machines generally use chains and sprockets (as in a bicycle), or belts and pulleys, or gears. In a later chapter we shall show how the speed of an automobile can be increased (and also decreased) by the proper use of gears.

Things to Remember

Fixed pulleys change the direction of a force whereas *movable pulleys* give a gain in force.

The *mechanical advantage of a pulley system* equals the number of supporting strings.

The *mechanical advantage of a wheel and axle* equals the circumference of the wheel divided by the circumference of the axle.

A *screw* is an adaptation of an inclined plane; it is a spiral inclined plane.

The *mechanical advantage of a screw* is low because considerable friction is essential in the operation of a screw.

Three *useful purposes of a machine* are: [**1**] it may increase the applied force, [**2**] it may change the direction of the applied force, [**3**] it may increase the speed of the applied force.

Questions

Part A

1. An inclined plane was probably used in the construction of the Great Pyramid. Explain how.
2. Draw diagrams to show [**a**] a fixed pulley, [**b**] a movable pulley.
3. By reference to a pulley system explain what is meant by the phrase "What is gained in force is lost in speed."
4. What is the advantage of [**a**] a fixed pulley, [**b**] a movable pulley?
5. Give two examples of common applications of a wheel and axle, one which gains force and the other which loses force.
6. A screw is an adaptation of an inclined plane. Explain why.
7. What is meant by the pitch of a screw?
8. Why is friction essential in the operation of a jackscrew?

Part B

9. Explain clearly why the mechanical advantage of a single movable pulley is 2.
10. Draw diagrams of the following pulley systems [**a**] one movable and one fixed, [**b**] two movable and two fixed, [**c**] two fixed and one movable, [**d**] one fixed and two movable. State the mechanical advantage in each case.
11. [**a**] Draw a wheel and axle.
    [**b**] Explain why this machine gains force and loses speed.
    [**c**] What adjustment would you make to this machine so that it would gain speed and lose force?

12. The mechanical advantage of a frictionless wheel and axle is $\frac{\text{radius of wheel}}{\text{radius of axle}}$. Can you explain why?
13. One screw has a pitch of 1/16 inch and another has a pitch of 1/32 inch. Each screw is bored into a piece of wood with the same screwdriver. Which needs the greater force (or effort)? Why?
14. Suppose the length of the handle of a jackscrew were reduced from 3 feet to 1 foot. How would this affect the applied force needed to lift a heavy load? Why?
15. [**a**] What is a wedge?
    [**b**] What is meant by the terms (i) effort, (ii) resistance, (iii) effort distance, (iv) resistance distance, as applied to a wedge?
16. What are the three main purposes of simple machines? Explain.

Problems

1. A load of 1 kilogram is raised by a pulley system that includes 2 fixed and 2 movable pulleys. The effort may have two different values depending on the arrangement of the thread. What are these two values? (Assume the pulleys are frictionless).
2. A force of 12 pounds is needed to raise a load of 20 pounds through 3 feet by means of a single movable pulley. Calculate [**a**] the actual mechanical advantage, [**b**] the distance the force moves, [**c**] the input work, [**d**] the output work, [**e**] the efficiency, and [**f**] the work done against friction.
3. If it takes one second to raise the load in Question 2, compute [**a**] the output power, [**b**] the input power.
4. The diameters of a wheel and axle are 12 inches and 4 inches. An effort of 10 pounds on the wheel raises a load of 24 pounds on the axle a distance of 3 feet. Compute [**a**] the theoretical mechanical advantage, [**b**] the actual mechanical advantage, [**c**] the effort distance, [**d**] the input work, [**e**] the output work, [**f**] the efficiency, [**g**] the work done against friction.
5. A load of 1 ton is raised by a jackscrew with a handle of length 2½ feet and a pitch of screw of 1/7 inch. Compute the effort needed to raise the load assuming [**a**] the jackscrew is frictionless, [**b**] the efficiency is 40 per cent.

Things to Do

A Pulley System that Gives a Gain in Speed

Arrange a pulley system as shown in Fig. 4-20. Before operating the pulley compute [**a**] the mechanical advantage and [**b**] $\frac{\text{resistance distance}}{\text{effort distance}}$.

Now pull down on the spring balance attached to the movable pulley. You will be surprised at the large effort needed to raise a load of 1 kilogram or 1 pound. The effort is much greater than the resistance; the force put into the machine is less than the force derived from it; there is a loss in force. Compute the mechanical advantage from the effort and the resistance.

Now compare the effort speed with the resistance speed. The speed of the load is much greater than the speed of the hand. Therefore, the machine gives a *gain* in speed.

It should now be apparent that a machine may give a gain in force or in speed, but not in both.

5

Levers

Probably the first machine ever used by man was a lever. To understand how levers work, let us first investigate how a meter stick suspended at its center can be balanced by hanging unequal weights at different distances from its center.

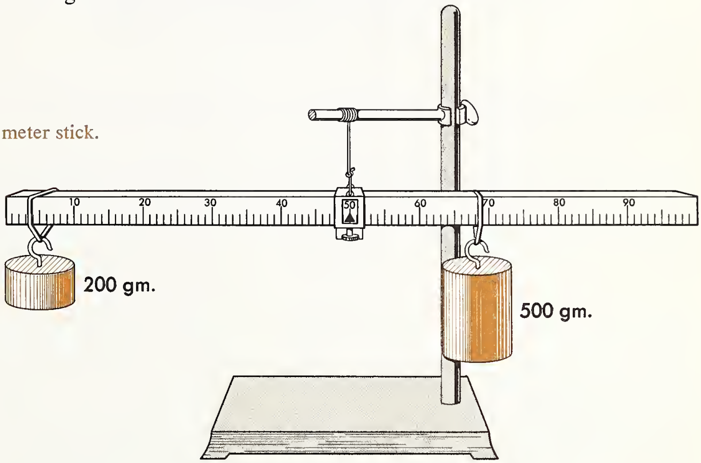

Fig. 5-1. Balancing a meter stick.

Experiment

5-1. Balancing a meter stick

Support a meter stick at the 50-centimeter mark by means of a clamp fastened to a rod supported on a stand as shown in Fig. 5-1. Using a loop of thread, suspend a 200-gram weight near the left end of the meter stick. Now suspend a 500-gram weight on another loop of thread. Place this weight on the right of the meter stick and adjust its position until the stick is balanced. Measure the distance of each weight from the point of support, or fulcrum.

Note that these distances are not equal, but the product of one weight and its distance from the fulcrum is equal to the product of the other weight and its distance from the fulcrum. Now place the 200-gram weight 40 centimeters from the fulcrum and move the 500-gram weight until the lever is balanced. Measure the distances from the fulcrum to the weights and again compute the products of each weight and

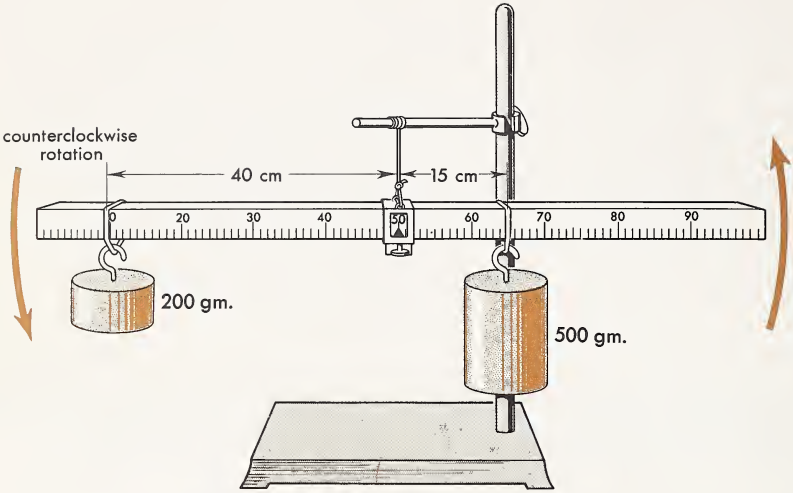

Fig. 5-2. This meter stick will rotate in a *counterclockwise* direction since the left-hand weight times its distance from the fulcrum (200 gm. × 40 cm.) is greater than the right-hand weight times its distance from the fulcrum (500 gm. × 15 cm.).

its distance from the fulcrum. Notice that again these products are equal. The fact that these products are always equal is one of the basic laws of balance (or ***equilibrium***, as it is usually called).

Moments

The product of a force and its distance from a fulcrum is an important quantity. We will investigate it further in the following experiment.

Experiment

5-2. Clockwise and counterclockwise rotation

Using the apparatus described in Experiment 5-1, again hang the 200-gram weight 40 centimeters to the left of the fulcrum. Suspend the 500-gram weight 15 centimeters to the right of the fulcrum. The 200-gram weight moves downward. Now move the 500-gram weight so it is 17 centimeters to the right of the fulcrum. The 200-gram weight now rises.

When the 200-gram weight is rising, the meter stick is rotating about its fulcrum as a center or ***axis***. This is called a ***clockwise*** rotation because the ends of the meter stick are going around the fulcrum in the same direction as the hands of a clock. When the 200-gram weight is moving downward, the rotation of the stick is ***counterclockwise***—opposite to the rotation of the hands of a clock.

Now consider the products of the weights and their distances from the fulcrum in this experiment. When the stick rotated counterclockwise (Fig. 5-2), the right-hand weight times its distance from the fulcrum was 500 × 15 = 7500, whereas the left-hand weight times its distance from the fulcrum was 200 × 40 = 8000. The side that moved down was the side where the product of weight and distance was greatest.

Similarly, when the 500-gram weight was moved to a point 17 centimeters to the right of the fulcrum, the stick rotated clockwise (Fig. 5-3) and the weight-distance product on the right-hand side was 500 ×

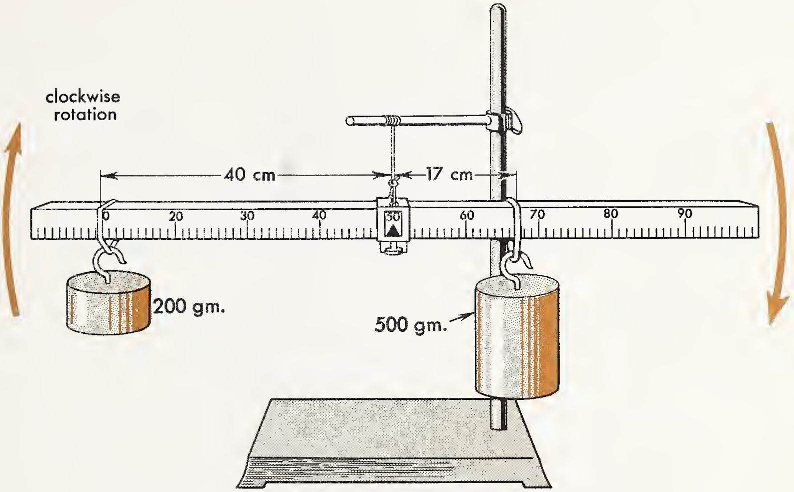

Fig. 5-3. This meter stick will rotate in a *clockwise* direction since the right-hand weight times its distance from the fulcrum (500 gm. × 17 cm.) is greater than the left-hand weight times its distance from the fulcrum (200 gm. × 40 cm.).

17 = 8500, which was greater than the product 8000 on the left-hand side. Again, the side that moved down was the side where the product of weight and distance was greatest.

We see that the hanging weights tend to make the stick rotate. This tendency of a weight (or force) to make an object rotate about a fulcrum is called a *moment* of a force. It is measured by the product of the force and its distance from the fulcrum. A weight hung to the right of the fulcrum produces a *clockwise moment* and a weight hung to the left of the fulcrum produces a *counterclockwise moment.* When both a counterclockwise and a clockwise moment act on a meter stick, it rotates in the direction of the larger moment. If the clockwise and counterclockwise moments are equal, there is no rotation. The stick is balanced; it is in equilibrium, as we found when we balanced a meter stick in Experiment 5-1. These effects are summarized in the *principle of moments* which may be stated as follows: *If the clockwise moment on an object equals the counterclockwise moment, the object is in equilibrium.*

Levers

Suppose we now consider a meter stick supported on a pencil as a fulcrum, as shown in Fig. 5-5. The stick is now being used as a machine to lift a heavy load (R), a 1-kilogram weight, by applying a small effort (E) at the other end of the stick. This is a lever, and we can use what we have learned about moments to predict how much effort is needed to lift the kilogram weight. To balance the weight exactly, the clockwise moment must equal the counterclockwise moment.

$$E \times d_E = R \times d_R$$
$$E \times 80 = 1 \times 20$$

Solving this for the effort (E) gives

$$E = \frac{1 \times 20}{80} = 0.25 \text{ kilogram.}$$

We see that the meter stick, used in this way, has a mechanical advantage of

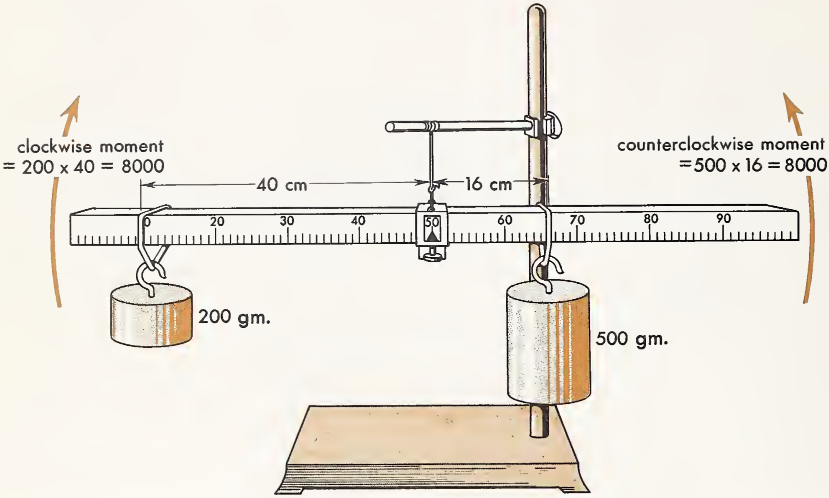

Fig. 5-4. If the clockwise moment equals the counterclockwise moment, the meter stick is balanced.

$$\frac{R}{E} = \frac{1.00 \text{ kg.}}{.25 \text{ kg.}} = 4$$

How could we increase the mechanical advantage of this lever? Look at the lever in Fig. 5-6. When the rock is balanced

$$Rd_R = Ed_E$$

and the mechanical advantage is

$$\frac{R}{E} = \frac{d_E}{d_R}$$

Clearly, if we make d_E large and d_R small by moving the fulcrum close to the rock, $\frac{d_E}{d_R}$ will become large and we will have a large mechanical advantage. For example, suppose we wish to lift a 300-pound rock, and the pole is 10 feet long. If we place the fulcrum 2 feet from the rock, d_R is 2 feet and d_E is $10-2 = 8$ feet. The mechanical advantage is

$$MA = \frac{d_E}{d_R} = \frac{8}{2} = 4$$

and the effort needed to lift the rock will be only $\frac{1}{4}$ of the resistance, or

$$\frac{1}{4} \times 300 = 75 \text{ lb.}$$

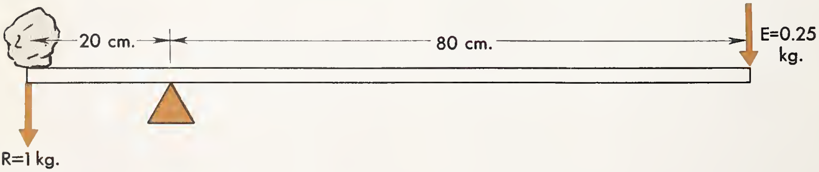

Fig. 5-5. A meter stick used as a lever.

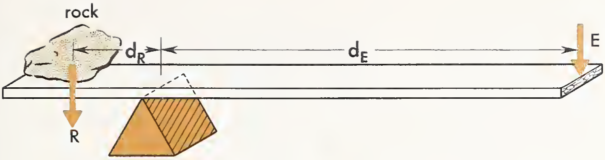

Fig. 5-6. The mechanical advantage of this lever is $\frac{d_E}{d_R}$.

The Center of Gravity

In both the levers we have just described (the meter stick lifting a 1-kilogram weight and the pole lifting a 300-pound rock), we would find, if we actually set up and used these levers, that our predictions of the effort needed to lift the load would not be quite correct. The reason for this is that we have not taken into account the weights of the meter stick and the pole.

How can we take the weight of a lever into account in order to correctly predict the effort needed to lift a given resistance? To find out, let us investigate the moment produced by a meter stick when it is supported by a fulcrum placed first at one point and then at another.

Experiment

5-3 The center of gravity of a meter stick

Support and balance a meter stick from a clamp as in Experiment 5-1. When the stick is balanced with the clamp at the 50-centimeter mark, the weight of the stick produces both a clockwise moment and a counterclockwise moment that are equal to each other. We can see that this is true because the clockwise moment produced by the weight of each centimeter of the meter stick to the right of the 50-centimeter fulcrum is exactly balanced by the counterclockwise moment of a centimeter of the meter stick at the same distance to the left of the fulcrum (see Fig. 5-7).

Since there is no net moment, either clockwise or counterclockwise, we can also argue that all the weight of the meter stick acts as though it were concentrated at the 50-centimeter mark (the fulcrum) where it would produce no moment. Why would a force at the fulcrum produce neither a clockwise nor counterclockwise moment? A force at this point acts directly through the fulcrum, and the distance from the force to the fulcrum is therefore zero. The moment of this force, which is the product of the force and its distance from the fulcrum, must also be zero, since anything times zero is equal to zero.

Let us test this argument by moving the

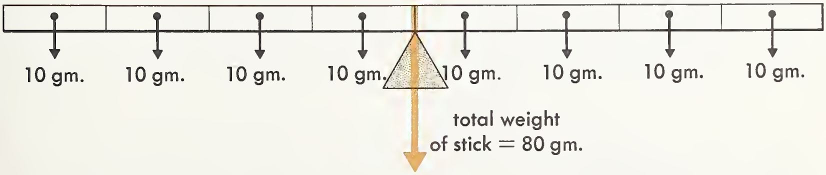

Fig. 5-7. The weight of each small equal piece of the balanced meter stick is 10 gm. Each 10-gm. piece on the left side of the fulcrum produces a counterclockwise moment just equaled by the clockwise moment of a 10-gm. piece at the same distance to the right of the fulcrum. The net moment is therefore zero, just as if the whole weight of the stick acted at the center of gravity, directly over the fulcrum.

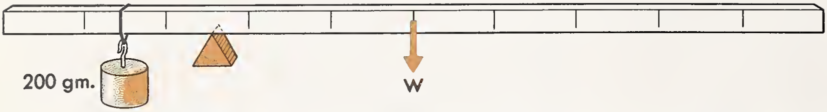

Fig. 5-8. The clockwise moment of the weight of the stick equals the counterclockwise moment of the 200-gm. weight.

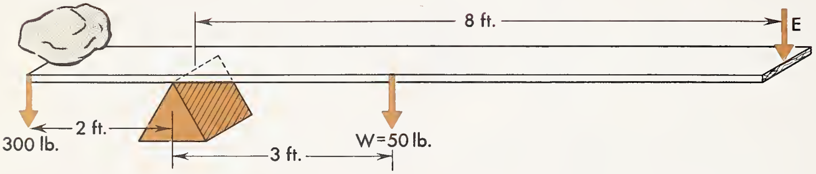

Fig. 5-9. Given the situation in this diagram, what is the effort force?

fulcrum to the 25-centimeter mark on the meter stick and use a 200-gram weight to restore balance. Find where the 200-gram weight must be placed to balance the stick.

Now calculate the moment produced by this 200-gram weight. Since the stick is balanced, the clockwise moment produced by the weight of the meter stick must be equal to the counterclockwise moment produced by the 200-gram weight (see Fig. 5-8).

Now remove the stick from its supporting clamp and weigh it on a balance. If you have made your measurements carefully, you will find that the weight of the stick is equal to the weight that must act at the 50-centimeter mark to give a moment equal to that of the 200-gram weight to balance the stick.

Thus we see that the whole weight of a lever acts at a certain point. This point is called the *center of gravity*. Of course, if the weight of the lever is small compared to the resistance it is lifting, the moment produced by the lever will be very small compared to that produced by the resistance. In such cases, we can neglect the weight of the lever and closely predict the effort needed to lift a given resistance without taking into account the weight of the lever.

Returning now to the pole used as a lever to lift a 300-pound rock, let us find the effort needed to lift the rock if the pole weighs 50 pounds.

If the pole is uniform (that is, if its thickness is the same all along its length), we can consider that its weight acts at its center. Since the fulcrum is 2 feet from the left end (Fig. 5-9), the weight of the pole is a downward force 3 feet to the right of the fulcrum. The moment due to the weight of the pole is therefore 50 × 3. Adding this clockwise moment to the clockwise

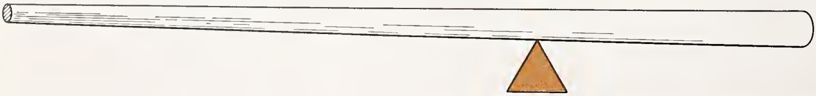

Fig. 5-10. The center of gravity (the point of balance) of a tapering pole is closer to the thick end than to the thin end.

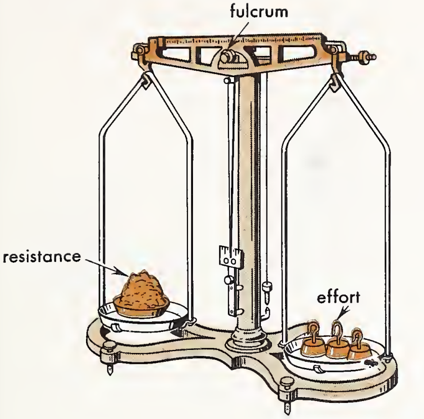

Fig. 5-11. An equal-arm balance is an example of a lever.

moment of the effort, and equating it to the counterclockwise moment of the 300-pound resistance we have

$$E \times 8 + 50 \times 3 = 300 \times 2$$

Solving for the effort, we find it to be

$$E = \frac{300 \times 2 - 50 \times 3}{8} = \frac{450}{8}$$
$$= 56.3 \text{ lb.}$$

In this case, we see that the weight of the lever aids the effort, making it less than the 75 pounds we had originally calculated on page 46.

We can always find where the center of gravity of an object is by supporting it on a fulcrum. The point where it balances is the center of gravity. A uniform object, like a meter stick, will of course have its center of gravity at the center; but a tapering pole, thicker at one end than the other (a pole cut from the trunk of a tree is a good example) will have its center of gravity closer to the thick end than the thin end (see Fig. 5-10).

Kinds of Levers

Fulcrum between effort and resistance. The simplest kind of lever is one in which the fulcrum is midway between the effort and the resistance as in a see-saw. If the board is 8 feet long, and if we push down on end A with a force of 30 pounds, the board is able to support a resistance of 30 pounds on end B. In other words, this lever merely changes the direction of the applied force.

An equal-arm balance used to weigh objects is an example of this kind of lever. That is, the weight of the object on one

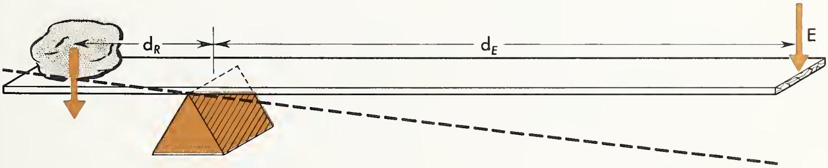

Fig. 5-12. This lever gives a gain in force but a loss in distance.

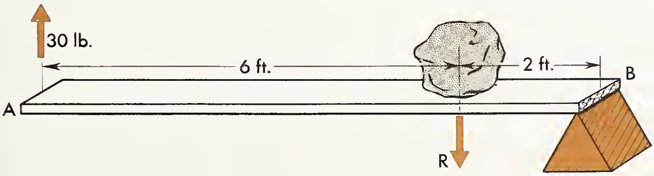

Fig. 5-13.

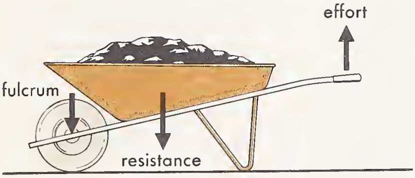

Fig. 5-14. In a wheelbarrow the fulcrum is at the center of the wheel.

pan is precisely the same as the sum of the weights on the other pan (see Fig. 5-11).

If the fulcrum is close to the resistance as shown in Fig. 5-12, and the weight of the lever is so small that it can be neglected, we have two unequal arms d_E and d_R, and the lever gives a gain in force. Notice, however, that the resistance (R) does not move up as far as the effort moves down. (Why not?) That is to say, the machine gives a loss in speed and distance. A lever of this kind is a crow-bar. Another example is a pair of tin shears.

Fulcrum at end of bar. In another kind of lever, the fulcrum is at the end of the lever as shown in Fig. 5-13. The lever is 8 feet long (its weight is small compared to that of the resistance), and the resistance is 2 feet from the fulcrum at B.

A lifting force of 30 pounds exerted at the end A will support a load of 120 pounds. How is this figure computed? The clockwise moment = 30 lb. × 8 ft. The counterclockwise moment is R lb. × 2 ft. Hence, by the principle of moments,

$$R \times 2 = 30 \times 8$$

$$R = \frac{240}{2} = 120 \text{ lb.}$$

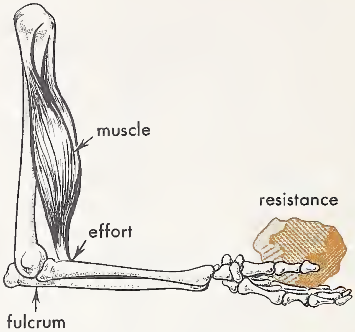

Fig. 5-16. The human forearm is a lever which gives a gain in speed.

A familiar example of this type of lever is a wheelbarrow as shown in Fig. 5-14. The mechanical advantage of a wheelbarrow is usually greater than 1. Why? What is the effect of the weight of the wheelbarrow?

Still a third type of lever is shown in Fig. 5-15. It is like that shown in Fig. 5-12 but the effort and resistance are reversed in position. This lever always has a mechanical advantage of less than 1 and gives a gain in speed. (Why?) Fig. 5-16 shows how the human forearm operates as a lever with a mechanical advantage of less than 1. This limitation is outweighed by the advantages of speed and easy co-ordination of movement that result from such an arrangement. In his evolution, man has developed a lever mechanism in his limbs that has enabled him to move about easily. We will see later how he has used his knowledge of levers and other machines to design complex mechanisms.

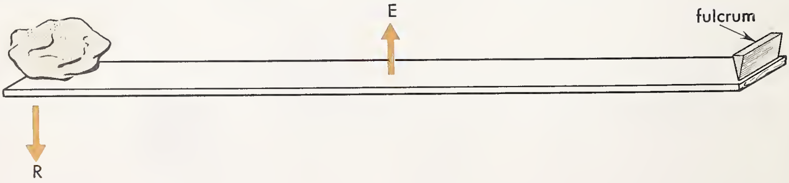

Fig. 5-15. This lever gives a gain in speed. Why?

Things to Remember

A *lever* is a rod or bar pivoted on a support called a fulcrum.

A *moment* is a turning effect and is defined as the product of the force and the distance from the fulcrum to the force.

In a *balanced lever* the clockwise moment equals the counterclockwise moment. This is called the *principle of moments*.

The mechanical advantage of a lever is equal to $\frac{d_E}{d_R}$, that is, the distance of the effort from the fulcrum divided by the distance of the resistance from the fulcrum.

The weight of a lever produces a moment as if all its weight were concentrated at one point—its *center of gravity*.

The center of gravity of a body is the point where it balances.

Questions

Part A

1. [**a**] What is a lever?
   [**b**] Draw a diagram of a lever to illustrate this definition.
2. Name three examples of levers that are not mentioned in this chapter.
3. [**a**] What is the moment of a force?
   [**b**] Illustrate your definition of moment by referring to the force applied to the handles of a wheelbarrow.
4. How can you tell when a force produces a clockwise moment?
5. Draw a lever with a mechanical advantage of less than 1.
6. What is meant by the term "center of gravity"?

Part B

7. Which machine do you suppose man invented first, a lever or an inclined plane? Give reasons for your answer.
8. [**a**] What is the principle of moments?
   [**b**] How could you verify this principle by experiment?
9. "What is gained in force is lost in speed." Explain how this statement applies to a lever.
10. In a lever $\frac{\text{output work}}{\text{input work}} = \frac{\text{output moment}}{\text{input moment}}$. Why?
11. Explain why the mechanical advantage is greater than 1 in a pair of shears, but less than 1 in a pair of scissors.
12. What is the mechanical advantage of the lever in Fig. 5-15?

Problems

1. A meter stick is balanced at its midpoint. When a 500-gram object is suspended at the 35-centimeter mark on the stick, an object of unknown weight must be suspended at the 80-centimeter mark to restore balance. What is the weight of the object?

2. Weights of 300 pounds and 200 pounds are made to balance at the ends of a 100-pound 10-foot plank. How far is the fulcrum from the 300-pound weight?
3. A rod, 7 feet long, is supported on a fulcrum 2 feet from one end. A load of 40 pounds at the end of the short arm is balanced by a force applied at the end of the long arm. Compute [**a**] the clockwise moment, [**b**] the counterclockwise moment, [**c**] the applied force, [**d**] the mechnical advantage.
4. [**a**] A 10-foot board weighing 10 pounds acts as a lever when a fulcrum is placed 3 feet from the left end. A 140-pound boy sits on this left end and another boy sits on the right end to balance the lever. Find the weight of this boy. Draw a diagram.
   [**b**] The fulcrum is now moved one foot to the left and the 140-pound boy is balanced by a bag of sand weighing 80 pounds. Where is the bag placed?
5. A balanced meter stick weighing 50 grams supports a 200-gram weight on the 10-centimeter mark and a 500-gram weight on the 80-centimeter mark. The stick and weights are supported by a spring balance. [**a**] What is the reading of the spring balance? [**b**] Where is the spring balance placed on the meter stick?
6. A 10-foot crowbar is used to lift a 200-pound rock, a stone 2 feet from the load being used as a fulcrum. [**a**] If the mechanical advantage is 4, compute the effort needed to lift the rock. [**b**] If the rock is raised 6 inches, compute (i) the distance the effort moves, (ii) the input work.
7. The ends of the handles of a wheelbarrow are 4 feet from the wheel axle and the weight of the wheelbarrow (20 pounds) acts at a point 1.5 feet from the axle. Where must a 200-pound object be placed in the wheelbarrow so that the handles can be lifted by a force of 75 pounds?

Things to Do

A lever that gives a loss in force

Tie a loop of strong string around a board (about 5 feet by 8 inches). Attach a spring balance to the loop of string (the spring balance should read up to about 25 pounds) and adjust the loop until the board is balanced horizontally. Read the weight of the board and mark its center of gravity.

Now arrange the board on a bench. A piece of metal tube (about a foot long) serves as a fulcrum. Weigh a brick with the spring balance and then place it on the board about 4 feet from the fulcrum. Place the loop about 2 feet from the fulcrum and attach the spring balance to the loop.

Compute the force needed to turn the board about the fulcrum to a horizontal position.

Now lift the spring balance. To prevent the left end from rising, place a brick on the board just above the fulcrum. It may also be necessary to press down on this brick with the left hand while raising the spring balance with the right hand. Read the spring balance when the board is horizontal. Compute the mechanical advantage of this lever.

Now interchange the positions of the resistance (the brick) and loop. Again compute the effort needed to lift the lever about the fulcrum, and then check your result by experiment. What is the mechanical advantage of the lever this time? Is this what you would expect?

6

Energy

Suppose we arrange the weights over a fixed pulley as shown in Fig. 6-1. The 200-gram weight is being held by the hand in a higher position than the 100-gram weight, which is suspended on the other end of the thread. What will happen if the 200-gram weight is released? We know from experience that the 200-gram weight will fall and that the 100-gram weight will rise. But work is done when the 100-gram weight is raised. Why? In other words, the pulley system shown in Fig. 6-1 is ready to go to work; or, as we usually say, this pulley system possesses energy. What, then, is energy? ***The energy of a body is defined as its capacity to do work.***

Kinetic Energy

We can think of many examples of devices capable of doing work, devices that possess energy. Suppose, for example, we are traveling by automobile at a comfortable speed of 40 miles an hour when we run head on into a stationary truck. We find, to our dismay, that our moving automobile possessed considerable energy, some of which damaged the truck and some of which wrecked our car. Energy possessed by bodies because of their motion is called ***kinetic energy***. Or, expressed another way, we can say that ***kinetic energy is energy due to motion***. As you know, the faster the car moves, the greater is the damage done when it hits the truck; that is, the greater is the amount of work done. Thus, ***the greater the speed of a body, the greater its kinetic energy.***

A baseball in flight also has kinetic energy. If you catch the ball in your mitt, it will push back your hand, and the mitt will be warmed by the impact. A moving hammer is used to drive a nail in wood. Work has to be done in forcing the nail through

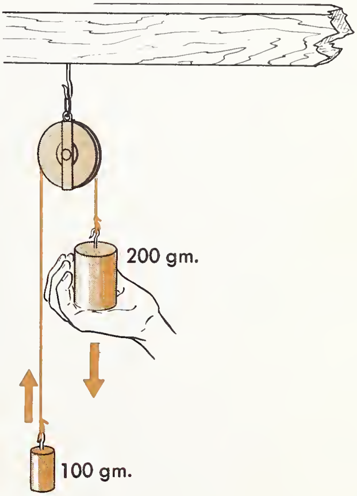
200 gm.
100 gm.

Fig. 6-1. This pulley system possesses energy and is capable of doing work.

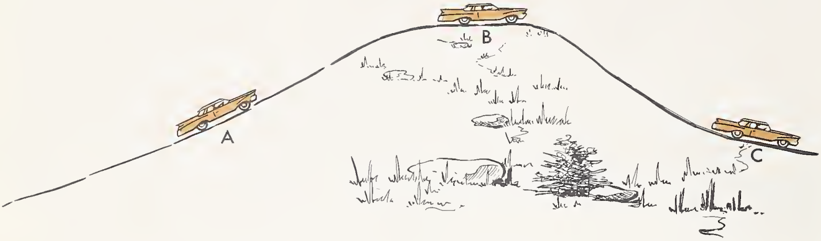

Fig. 6-2. In position A the chemical energy of gasoline is being used to push the car up the hill; in position B the car has its maximum potential energy; in position C some of the potential energy has been transformed into kinetic.

wood. The moving hammer supplies the energy to do this work and, in doing so, it loses its kinetic energy. Falling water also has kinetic energy. Some of the water at Niagara Falls flows down steep conduits through a height of almost 140 feet. The rushing water rotates turbines at the bottom of the conduit. The rotating turbines in turn operate electric generators which supply electricity to many towns and industries in Ontario.

Potential Energy

Let us now return to the automobile, cruising at 40 miles an hour before its impact with the truck. If we come to a steep gradient we merely depress the accelerator pedal and we climb the hill. Suppose we stop the car at the top of the hill and turn off the engine. We know that the car, because of its height, possesses energy even when at rest, and that this energy is capable of taking the car down the far slope (see Fig. 6-2), at high speed without the help of the engine. That is to say, at the top of the hill energy is stored in the car. This energy is *available* for doing work. It clearly is not kinetic energy since there is no motion; it is called *potential energy*. Similarly, the 200-gram weight suspended above the table as shown in Fig. 6-1 also possesses potential energy. However, a mass lifted vertically is not the only example of potential energy.

High pressure steam in a boiler also has this type of energy. This steam can be used to drive a piston back and forth in a cylinder and so drive a locomotive. Gasoline also possesses potential energy. Gasoline is mixed with air and explodes in the cylinder of an automobile. The energy released in the explosion drives the piston of the automobile engine which, in turn, moves the car. We see that ***potential energy*** can assume different forms and it is usually defined as ***the energy a body possesses in virtue of its position or condition.***

Transformation of Energy

Again let us return to the automobile climbing the hill. The chemical potential energy of the gasoline was used to push the car uphill against the force of gravity. Energy that was stored in the gasoline was, therefore, transferred to and stored in the automobile. That is to say, potential energy of condition (in gasoline) is transformed into potential energy of position (in the car). If the car now coasts down the far slope of the hill, still another energy transformation takes place. What is the nature of this transformation? As the car loses height it gains speed; or, expressed another way, as the car loses potential energy it gains kinetic energy. Probably the simplest example of transformation from potential to kinetic energy is a swinging pendulum as shown in the following experiment.

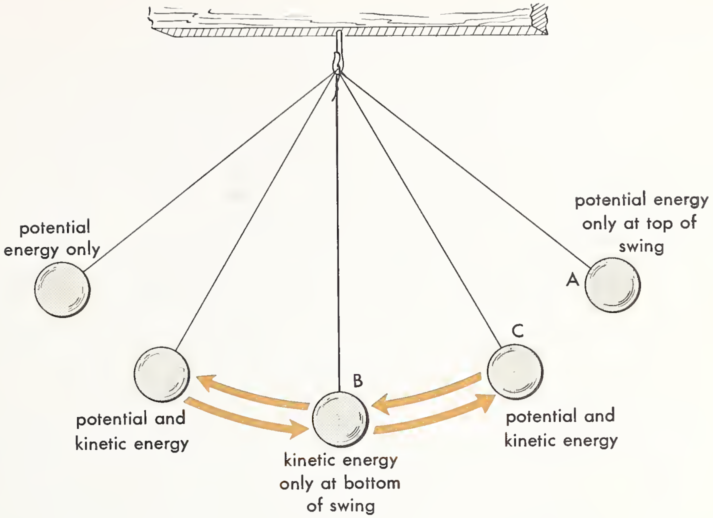
potential energy only
potential energy only at top of swing
A
C
B
potential and kinetic energy
kinetic energy only at bottom of swing
potential and kinetic energy

Fig. 6-3. A swinging pendulum is an example of transformation of energy.

Experiment

6-1. Transformation of energy in a simple pendulum

Hang a pendulum from a rod supported by a stand and clamp (see Fig. 6-3). Displace the bob of the pendulum and then release it. The bob swings back and forth for some time.

What are the energy changes in the swinging pendulum? At the top of its swing (in position A) the bob is at rest for a moment: it has no kinetic energy; all its energy is potential. At the bottom of the swing (in position B) it is in its lowest position. Therefore it has the least potential energy but the greatest kinetic energy, and it moves through this position with the greatest speed. Thus in the downward swing the bob loses potential energy but gains kinetic; in the upward swing the reverse is true. What of the energy of the bob in position C, midway between A and B? It should now be apparent that the energy at C is part potential and part kinetic, the potential energy is less than in position A and the kinetic energy is less than in position B. Why? It should also be apparent that as the bob is swinging back and forth energy is neither gained nor lost, but merely transformed (except for the small amount of energy lost as heat due to friction with the air).

Still another example of the conversion of kinetic energy to potential occurs when a ball is thrown vertically upward into the air (see Fig. 6-4). At the moment the ball leaves the hand it has its greatest kinetic energy. As the ball rises it slows down because kinetic energy is being changed to potential energy. Eventually, at the top of its flight, the ball stops for a moment. In this position the ball has no kinetic energy; all the original kinetic energy has now been converted into potential energy.

These changes are then reversed: the ball loses height and gains speed so that when it returns to the hand its kinetic energy is the same as when it was thrown upward. Notice that the changes from kinetic energy to potential or from potential to kinetic are gradual changes; they do not occur suddenly.

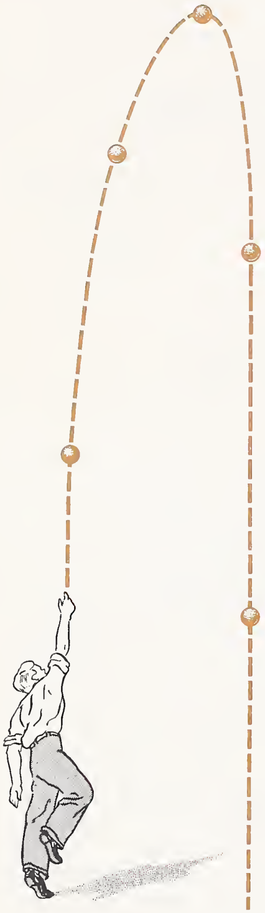

Fig. 6-4. A ball thrown upward loses kinetic energy as it rises but gains potential energy.

The Conservation of Energy

The total amount of energy possessed by the baseball is the same at all points in its flight. Why is this? As the ball rises it loses kinetic energy but gains a corresponding amount of potential energy. Therefore, there is neither a net gain nor loss of energy. This situation applies to all transformations of energy, whatever they be. It is a law of nature that there is no increase or decrease in the total amount of energy whenever energy is changed from one kind to another. This important natural law is called the ***law of conservation of energy*** and it is usually stated as ***Energy can neither be created nor destroyed.***

Heat Energy

Let us again go back to our automobile. Suppose we suddenly apply brakes to the car traveling at 40 miles an hour. The car slows down; it loses kinetic energy. What happens to this kinetic energy? We know that the energy is not lost. Then what happens to it? The brake drums become quite hot when a car is suddenly stopped, and we therefore conclude that kinetic energy has been changed to heat. This heat escapes into the air as the brake drums cool off. In other words, ***heat is a form of potential energy***. It can do work and we shall discuss numerous examples of the conversion of heat into work in later chapters, particularly when we consider the operation of a locomotive, an automobile, and an airplane. In the following experiment potential energy is changed to kinetic energy which, in turn, is changed to heat energy.

Experiment

6-2. To change kinetic energy to heat energy

Place about a pound of lead shot in a beaker. Immerse the bulb of a thermometer well within the lead shot and read the temperature. Now pour the lead shot into a long cardboard tube (3 feet is a good length) closed by a stopper at one end. Close the open end of the tube with another stopper.

Place a hand at either end of the tube and invert it so that the shot falls from top to bottom. Repeat this operation rapidly about 50 times. Now pour the shot into the beaker and again immerse the bulb of the thermometer well within the shot. The thermometer slowly rises for 2 or 3 minutes and eventually shows a rise of at least 3 degrees.

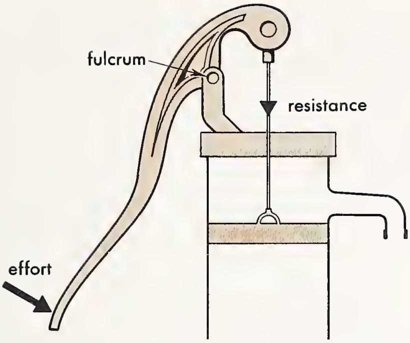

Fig. 6-5. A pump handle is a lever which gives a gain in force.

How can we account for the rise in temperature? We do work in lifting the shot and this work is then stored in the lead shot as potential energy. Gravity then pulls the shot down the tube, and the potential energy is changed to kinetic. At the bottom of the tube the shot is suddenly stopped and its kinetic energy is converted into heat. The generation of heat is made evident by the rise in temperature shown by the thermometer. By the same reasoning, we would except a rise in temperature to occur if we pound a nail with a hammer. This experiment is worth trying.

Potential energy must usually be changed to kinetic energy before work can be done. If we reconsider the various examples of energy transformations, we must be aware of the fact that potential energy is a means of ***storing*** energy, whereas kinetic energy is a means of ***expending*** energy, that is, of doing work. A device which possesses potential energy is unable to do work unless its potential energy is first changed to kinetic. A compressed spring has potential energy. But to do work the spring must be released. When released, the spring moves and, in moving, does work. Or consider a pile driver used to drive piles into boggy ground. The hammer of the pile driver is raised a considerable distance. In this position, however, it does no work. Work is done only when the hammer falls and strikes the top of one of the piles.

Energy and Machines

With these new ideas on energy, let us take another look at machines. A machine is a device that transfers energy from one place to another—this is the main purpose of a machine (see Fig. 6-5). Let us consider a pump handle as an example of a machine. A pump handle is a lever. Why? If we push down on the handle, the piston (and also some water) is raised. In pushing down the handle we do work; we put energy into the lever. This energy is transferred from our hand to the piston (and water) via the pump handle. Similarly, we can trace the transfer of energy through any machine.

From the law of conservation of energy it follows that the energy put into a machine equals the energy derived from it. If the machine is frictionless, the input work equals the output work. If, however, there is some friction in the machine (as there always is), then some of the input energy is changed to heat (as in the case of the brake drums) and is lost as far as its usefulness is concerned. Thus we can say that the input energy equals the useful output energy plus the energy lost as heat. This is just another way of stating the law of machines which, as you recall, is ***input work equals output work plus work done in overcoming friction.***

Man has shown a great deal of ingenuity in changing the energy put into a machine so that it can be utilized to his advantage. In a later chapter we shall read how he has designed complex combinations of machines to make automobiles and airplanes which change the potential energy of gasoline to mechanical energy, which, in turn, propels the vehicles at high speed.

Mechanical energy of a water turbine can be converted to electrical energy by means of a machine called a generator. Electricity is an important form of energy and, when transformed to mechanical energy by a motor, it performs countless labor-saving tasks.

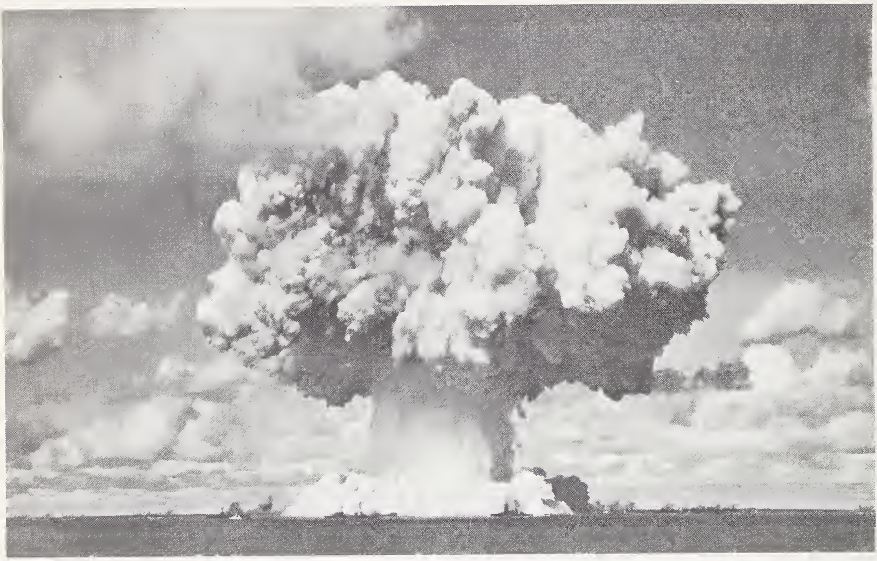

Fig. 6-6. In this underwater explosion, a single atomic bomb sent a column of water, weighing almost 10 million tons, up to a height of more than half a mile.

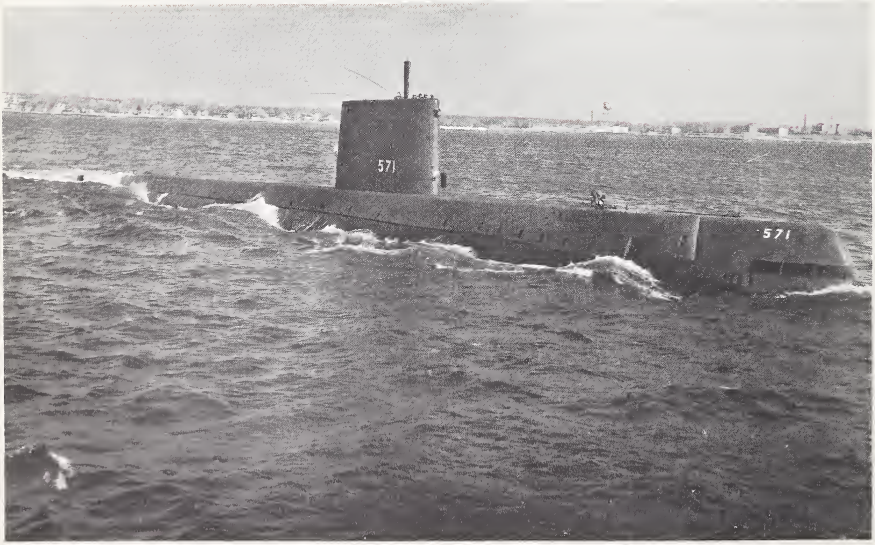

Fig. 6-7. This submarine is driven by atomic energy. It traveled more than 60,000 miles without refueling.

Atomic Energy

Still another form of potential energy is atomic energy. This is the energy that has become available to man only during the twentieth century. Unfortunately, atomic energy was first used for destructive purposes, in bombs where the released energy is out of control. Scientists have learned to control this form of energy and convert it into useful electrical energy.

What is atomic energy? It is derived from the nuclei of atoms. If the nuclei of large atoms (uranium atoms) are split, vast amounts of energy are released. On the other hand, if the nuclei of the smallest atoms (hydrogen atoms) are fused together to make larger atoms, vast quantities of energy are also released.

Uranium atoms can be split in an atomic furnace called a reactor and the heat released can be used to convert water to steam which in turn drives an electric generator. The electrical energy formed in this way can be used as a source of power. For example, some surface ships and some submarines are driven by atomic energy released in reactors.

Scientists have a good deal to learn before they can control the power released by hydrogen atoms. This will be one of the achievements of the future. But although the controlled use of this vast store of energy from hydrogen atoms has not been achieved yet, strangely enough, the whole of mankind benefits from this source of energy. The energy of the sun is due to the fusing together of hydrogen atoms. The sun is 93 million miles away, but its atomic heat warms the earth–indeed, all life on earth depends upon it and without it all life on earth would perish.

Things to Remember

The *energy* of a body is its capacity to do work.

Kinetic energy is energy due to motion.

Potential energy is the energy due to position or condition.

The *law of conservation of energy* states that energy cannot be created or destroyed.

Heat, electricity, and chemical energy are all forms of potential energy.

A *machine* is a device that transfers energy from one place to another.

In any machine, the *input energy* equals the useful output energy plus the energy changed to heat.

Questions

Part A

1. What is energy?
2. What is kinetic energy? Give an example.
3. What is potential energy? Give an example.
4. Describe a simple example of the conversion of [**a**] kinetic energy to potential, [**b**] potential energy to kinetic.
5. What is meant by chemical potential energy?
6. State the law of conservation of energy. What does this statement mean?

7. Give an example of the conversion of [a] kinetic energy to heat, [b] heat to kinetic energy.
8. A machine is a device that transfers energy. Give an example of this by reference to a wheel and axle.

Part B

9. Describe the energy changes that take place when water at the top of Niagara Falls moves to the bottom of the falls.
10. Describe the energy changes that take place when a baseball is struck by a bat.
11. Describe the energy changes that take place when the cigarette lighter in an automobile is used.
12. Describe the main energy transformation in a diesel locomotive.
13. Explain what is meant by the statement that potential energy must be changed to kinetic energy before work can be done.
14. How does the law of conservation of energy apply to a jackscrew?
15. What is an atomic reactor and what is its purpose?
16. The heat from the sun is derived from atomic energy. Explain why.

Things to Do

Heat from Friction

1. Grip a pencil tightly with the thumb and the first and second fingers. Pull the pencil rapidly through the fingers. If this is repeated in quick succession a dozen or so times the fingers become uncomfortably hot. How do you account for the heat that is generated?
2. Boy Scouts learn to make a fire by friction (without matches). To do this a wooden drill is rapidly rotated on a board, and the heat of friction ignites a tinder of dry combustible material. Look it up in the Boy Scout handbook and try the experiment yourself.

7

Gases and the Kinetic Theory

If a bottle of household ammonia is opened in a room several feet from your nose, you will soon smell the strong characteristic odor of ammonia gas. If there are any drafts or air currents in the room and the air is moving from the bottle toward you, you will smell the ammonia within a few seconds after the bottle is opened. But, even if the air in the room is still and not moving, you will smell the ammonia in a few minutes. To explain what has happened we assume that ammonia gas is made up of very tiny invisible particles that move about freely in all directions. When these particles, called ***molecules*** of ammonia, reach the nose, they stimulate the nerve endings in the nose and produce the sensation we recognize as the characteristic odor of ammonia.

The motion of gas molecules can be shown by a simple experiment. We shall use two solutions, hydrochloric acid and

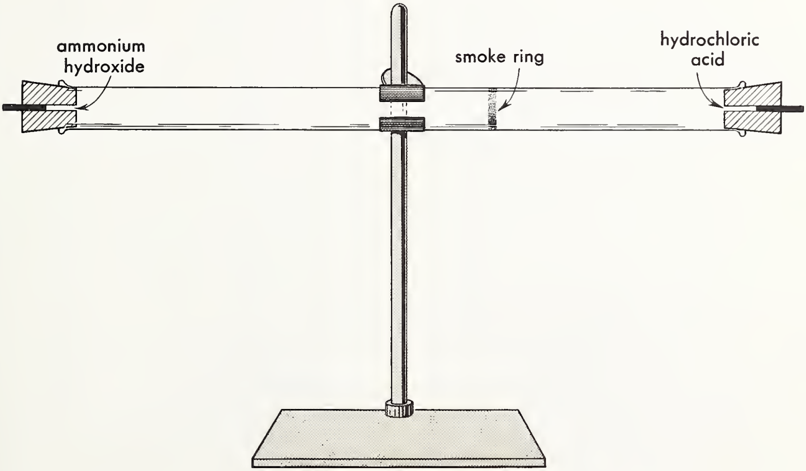

Fig. 7-1. This experiment proves that ammonia molecules travel faster than hydrogen chloride molecules.

ammonium hydroxide, for this purpose. Molecules of hydrogen chloride gas escape from hydrochloric acid, and molecules of ammonia gas escape from ammonium hydroxide. If these gas molecules meet they react chemically to form a white powder or "smoke."

Experiment

7-1. To show that gas molecules move

Take a glass tube about a yard long and about an inch in diameter; support it horizontally on a stand and clamp as shown in Fig. 7-1. Insert a short piece of glass rod halfway into the hole of a one-hole stopper. Put one or two drops of concentrated ammonium hydroxide into the "hole" in the stopper. Prepare another stopper in the same way but put one or two drops of concentrated hydrochloric acid into its "hole." Fit the stoppers tightly into the ends of the tube and look for the formation of a white "smoke" near the middle of the tube. After 10 minutes or so, the smoke appears about midway in the tube, but nearer the hydrogen chloride end than the ammonia end.

What do we learn from this experiment? It is apparent that gas molecules escape from each of the solutions and that they eventually meet and react. Notice, however, that the ammonia molecules travel a little further than the hydrogen chloride molecules. We therefore conclude that ammonia molecules travel faster than hyrogen chloride molecules.

How fast do gas molecules move? Since it took about 10 minutes for the gases to meet and react, we might conclude that gas molecules travel very slowly. But would this conclusion be justified? We must remember that the tube also contains air molecules. Moreover, there are many billions of them in every cubic centimeter of air. In other words, there must be a vast number of collisions between gas molecules in the tube every second, so that the motion of ammonia and hydrogen chloride molecules along one direction is hindered. The gas molecules move in a straight line for only very short distances (a tiny fraction of an inch) before colliding and changing direction as shown in Fig. 7-2. Even if they travel at high speeds, their motion in one direction would be slow because of frequent collisions. Air molecules, in fact, move at exceedingly high speeds, speeds of more than 1000 miles an hour!

In the experiment with the ammonia and

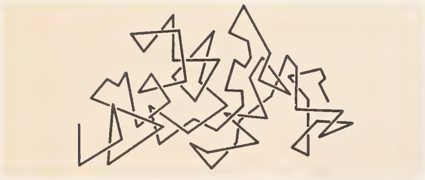

Fig. 7-2. The path of a gas molecule. The changing direction is caused by molecular collisions.

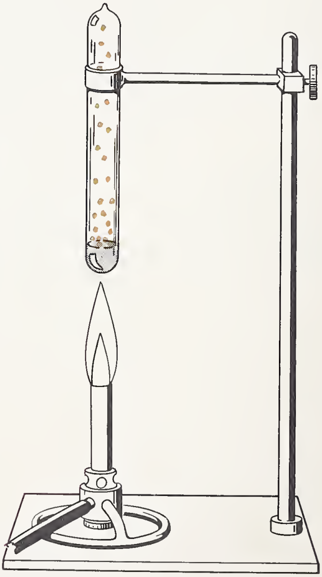

Fig. 7-3. The kinetic energy of mercury molecules at high temperatures lifts bits of glass to the top of the tube.

hydrogen chloride, the fact that the white smoke formed closer to the source of hydrogen chloride than to the source of ammonia showed that hydrogen chloride molecules apparently move more slowly than ammonia molecules. Hydrogen chloride molecules are known to be heavier than ammonia molecules and therefore, it seems reasonable to conclude that ***heavy gas molecules move more slowly than light gas molecules.*** More careful experiments with many different kinds of gas molecules do, in fact, show that this conclusion is correct.

The Speed of Gas Molecules and the Temperature of a Gas

If the temperature of a gas is raised, will the speed of its molecules be affected? We can find the answer to this question by doing an experiment.

Experiment

7-2. The effect of temperature on the speeds of gas molecules

The sealed glass tube shown in Fig. 7-3 contains bits of glass floating on the surface of some mercury. If the bottom of the tube is heated, the glass bits jump about violently, some of them reaching the top of the tube. How can this be explained?

When the mercury is heated some of it changes to a gas and the mercury gas molecules fly about and hit the glass bits. Since the mercury molecules are moving they have kinetic energy and when they collide with the bits of glass they are able to transfer kinetic energy to the glass. At a high temperature they have enough kinetic energy to lift the glass pieces to the top of the tube. Therefore, it appears that the kinetic energy of the molecules of a gas increases as the temperature of the gas rises. And, since the kinetic energy increases, it follows that the speeds of the molecules increase as the temperature of the gas is raised.

The Kinetic Theory

We now have a mental picture of a gas based on the motion of its invisible molecules. Starting with the idea that a gas is made up of tiny molecules that move about freely in all directions in the space they occupy, we have found that (1) they move very fast, colliding frequently with each other; (2) the higher the temperature of a gas, the faster its molecules move; (3) heavy molecules move more slowly than light molecules.

These assumptions concerning the motion of gas molecules are part of what is called the ***kinetic theory of gases*** ("kinetic" comes from the Greek word *kinesis,* meaning "motion"). This theory is a picture or model of a gas based on the assumption that it is made of tiny moving molecules, even though these molecules are too small to be seen. Like all theories, it helps to explain some of the things that happen in nature, and it often predicts other things that should happen in nature under certain conditions. We can then set up experiments and look for these predictions. If the results of the experiments confirm the predictions of the theory, we have learned something new about nature and have gained confidence in the theory. It must be remembered, however, that the predictions of a theory are only guideposts into the unknown, pointing the way to experiments that are the real proofs of our knowledge of how nature operates.

Gas Pressure

As an example of a prediction that can be made from the kinetic theory, let us consider the pressure exerted by a gas. Gas molecules are always on the move; they must collide, not only with each other but also with any surface in contact with the gas. These collisions should result in a force or pressure on the surface. Let us try to check this prediction by doing a simple experiment to see if we can detect such a force or pressure.

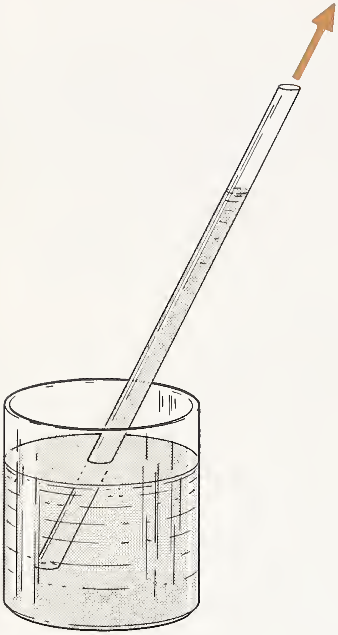

Fig. 7-4. If air is sucked out of the tube, water rises up the tube. Why?

Experiment

7-3. To show that a gas exerts pressure on a water surface

Dip one end of a glass tube, at least 1 foot long, into water in a beaker (see Fig. 7-4). Notice that the water level is the same inside the tube as outside. Now suck air out of the tube and observe that water rises in the tube. Why does the water rise?

When air is sucked out of the tube, many of the air molecules are removed from it. But air molecules in the atmosphere outside the tube are not affected. Therefore we assume that, in some way, these outside air molecules cause water to rise in the tube. How can this be? The kinetic theory suggests the answer. Moving air particles in the atmosphere strike the water surface and bounce off, exerting a force against the surface at the moment of impact (see Fig. 7-5). The force exerted by a single molecule is, of course, exceedingly small but, since there are many billions of molecules in a cubic centimeter of air, and since these molecules move very fast, there must be billions of molecular collisions upon every square centimeter of surface every second. This constant bombardment constitutes a steady force exerted upon the surface; this is the force that pushes water up the tube. Of course, the air molecules in the tube collide with the water in the tube, but since we have sucked out a large number of them, there are not enough collisions to overcome the force produced by the molecules of the outside atmosphere pushing water up the tube.

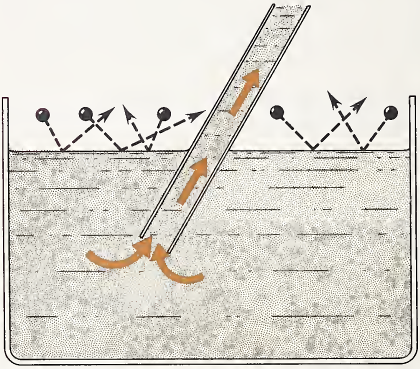

Fig. 7-5. Moving air molecules strike a water surface and bounce off, thereby exerting a steady force on the water surface that pushes water up the tube.

Gas Pressure is Exerted in All Directions

Since gas molecules move in all directions, we would expect that the gas pressure resulting from the impacts of these molecules should likewise be exerted in all directions. When we blow up a round rubber balloon we see immediately that such is the case; the balloon expands equally in all directions as the gas molecules push the rubber

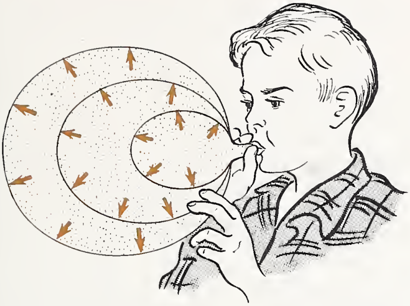

Fig. 7-6. As more gas molecules are blown into the balloon, the pressure inside increases and the balloon expands in all directions.

outward when their number inside the balloon is increased (see Fig. 7-6). So it is with all containers of gas; the pressure is exerted on all the surfaces of the container. The air molecules in a one-gallon tin, for example, exert pressure on the top and bottom as well as on the four sides.

Measuring Gas Pressure

It is convenient to measure gas pressure in terms of the force the bombarding molecules exert on a unit area of surface. Pressure is, in fact, usually defined as *the force acting on a unit area*. Thus, if a cylinder (Fig. 7-7) has a piston the area of which is 10 square centimeters and which contains a gas the molecules of which exert a force of 500 grams on the piston, the pressure exerted on the piston by the gas inside the cylinder is

500 gm./10 sq. cm. = 50 gm./sq. cm.

That is, each square centimeter of the piston exercises a force of 50 grams as a result of the collision of gas molecules with the piston.

It is usually difficult to measure gas pressure directly by measuring the force on a unit area. One common way of measuring gas pressure indirectly is to use a ***barometer***, a device that is particularly useful in measuring the pressure exerted by the molecules of the atmosphere of air that surrounds us.

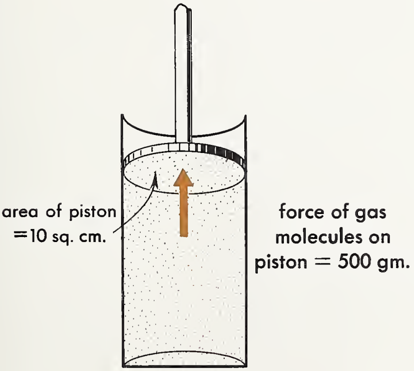

Fig. 7-7. Pressure of gas on piston $= \frac{500 \text{ gm.}}{10 \text{ sq.cm.}}$ = 50 gm/sq. cm.

Experiment

7-4. To make a simple barometer

Completely fill a glass tube with mercury. The tube should be closed at one end and should be about a yard long and about half an inch in diameter. Close the open end with the finger, invert the tube and place its open end below the surface of mercury in a dish or beaker, and then remove the finger (Fig. 7-8).

Notice that, as soon as the finger is removed, some mercury falls out of the tube. Why does this happen? The weight of the mercury in the tube exerts a downward pressure which tries to push mercury out of the bottom of the tube; the downward pressure of the atmosphere on the open surface of the mercury in the dish, on the other hand, tries to push mercury *up* the tube. When enough mercury has run out of the bottom of the tube so that these opposing pressures balance each other the mercury stops falling and stays at a constant height.

Notice the space above the mercury column in the barometer. Is there any air

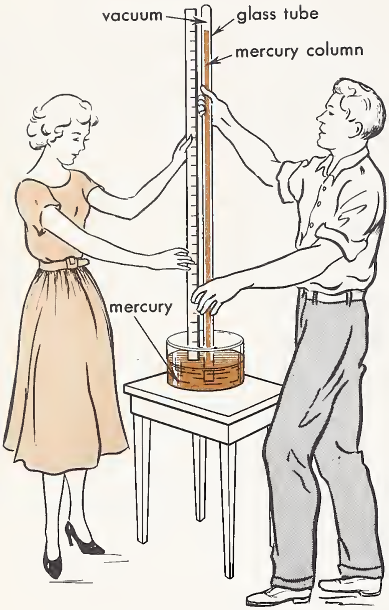

Fig. 7-8. A mercury barometer measures atmospheric pressure.

in this space? We can find the answer to this question by tilting the tube as shown in Fig. 7-8, making sure that the open end of the tube is kept below the mercury surface. Observe that, as the tube is tilted, the mercury level remains at the same vertical height but the space above the mercury becomes smaller. If the tube is tilted enough, the space will disappear altogether. This shows that the space does not contain air; it is empty. An empty space is called a *vacuum*. Now hold the tube in a vertical position and measure the height of the mercury from the surface in the dish to the top of the column. This height is about 76 centimeters (or 30 inches). We use this height as a measure of the atmospheric pressure. In this case we can say that *the pressure of the atmosphere is equivalent to the pressure of a vertical column of mercury about 76 centimeters or 30 inches high.* In terms of the force exerted on a unit area, a pressure of 76 centimeters of mercury is equal to about 15 pounds per square inch.

The Atmosphere

We must not think that a mercury barometer always gives the same reading. The pressure of the air varies slightly from day to day with changes in the weather and these variations in air pressure cause the mercury column to rise or fall through small distances. As you probably know, these variations in pressure are a part of the data used by weather forecasters in making weather predictions. When the barometer is rising (atmospheric pressure increasing) clear weather is usually approaching. When the barometer is falling, stormy weather is likely to be on the way.

If we carry a barometer to the top of a high mountain or up in an airplane, we find that the mercury column is not as high as at sea level. Why not? The pressure of the air decreases as we go to higher and higher altitudes. This is because at higher altitudes there is less air above us pressing down and a small air pressure is sufficient to support the air above us. If the air exerts less pressure, we would expect fewer molecules bombarding a surface in a second. Such is the case. In fact, at an altitude of 3½ miles, the air pressure is about one-half of the pressure at sea level. This means that each cubic meter of air contains only half as many molecules at an altitude of 3½ miles as at the earth's surface. Hence, at this elevation, only half as much air would enter our lungs at each breath as at sea level and we would have to breathe twice as fast. Six miles up (approximately 30,000 feet) the air is too thin to support life and, as you probably know, planes flying at such high elevations are equipped with pressurized cabins for passengers. Since there is little air outside the plane and the air inside is at the same pressure as at sea level, the force of the air pushing out must be much greater than the force of the air outside pushing in, and the body of the airplane must be strong enough to withstand this difference.

To get some idea of the force resulting from air at sea-level pressure we will do an experiment in which we will reverse the above situation. We will reduce the pressure inside a tin can to about the pressure of the atmosphere at 30,000 feet and see what the sea-level pressure on the outside of the can will do to the can.

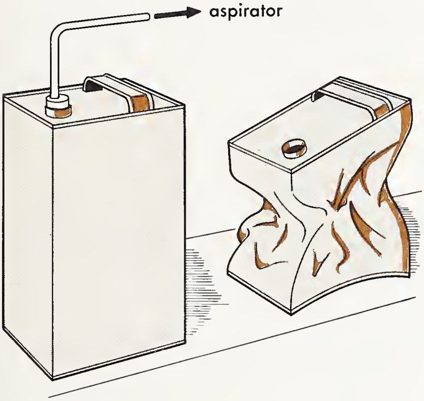

Fig. 7-9. If air is taken out of a tin can, it buckles and collapses.

Experiment

7-5. The force exerted by air at sea-level pressure

Place a short piece of glass tubing through a one-hole stopper, and fit the stopper into the outlet of a one-gallon tin can. Attach the tube to an aspirator and turn on the tap. In a few minutes the can begins to buckle and, eventually, it collapses completely as shown in Fig. 7-9.

What causes the can to collapse? When air is withdrawn, the pressure of the outside air against the can (15 pounds on every square inch) is much greater than the pressure of the air inside, and the can is not strong enough to withstand the inward thrust.

Atmospheric pressure is, of course, exerted on our bodies just as it is on the can. But we are not crushed by it; indeed, we are not even aware of it. This is because we inhale air. The blood and body tissues transmit the pressure of the inhaled air which acts as a counterpressure to the outside air.

Some Applications of Air Pressure

A large number of contrivances depend upon air pressure for their operation. To understand how some of these contrivances work let us first set up and operate the following simple device.

Experiment

7-6. A device to show gas pressure

Pour water into a flask until it is about one-third full. Push one end of a glass tube (at least 2 feet long) through one of the holes of a 2-hole stopper and push a right-angle bend through the other hole. Fit the stopper into the neck of the flask and arrange the apparatus as shown in Fig. 7-10.

1. Place the end of the right-angle bend (X) in the mouth and suck air out of the flask. Bubbles of air enter the flask through the water. Why is this? The air pressure in the tube (Y) is greater than the pressure in the flask (why?), and therefore air flows from the higher to the lower pressure.
2. With the mouth still at X, blow air into the flask, and quickly close the end X with the finger. Notice that water rises in tube Y. How can this be explained? The pressure of air in the flask is greater than atmospheric pressure outside and the excess pressure forces water up the tube.
3. Now place a short rubber tube over the end X and seal it with a pinch clamp. Place the end of tube Y in your mouth, blow down the tube and then take the tube out of your mouth. What happens? Why? Water rushes up tube Y, because air pressure in the flask was increased by blowing down the tube.
4. Release the pinch clamp. What happens? Why?

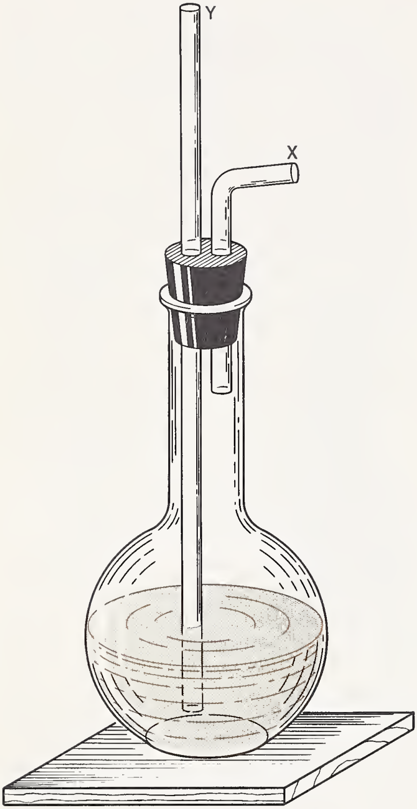

Fig. 7-10. A device to show gas pressure.

Suppose that we place an air-tight cover over a glass nearly full of water and pass a drinking straw through a small hole in the cover, sealing the straw to the cover with paraffin wax. Why is it now impossible to suck all the water out of the glass?

A rubber plunger on the end of a stick is often used to clear a drain-pipe that is blocked. How does this plunger work? The plunger is placed over the end of the drain pipe and the stick is then pushed down. As the stick is pushed down air in the plunger is compressed. Air molecules in the plunger are forced closer together and more of them bombard the surface of the water in the drain, thereby increasing the pressure on the water in the drain pipe and forcing the obstruction out.

A Water Barometer

We have discussed a mercury barometer. Mercury, however, is an expensive liquid. Would it be possible to use water instead of mercury? In other words, is there such a thing as a water barometer? You may have noticed that mercury is much heavier than an equal volume of water. Indeed, it is 13.6 times as heavy or, as we usually say, mercury is 13.6 times as dense as water. Hence, if water were used in a barometer its height would be 13.6 times the height of the mercury column. That is, its height would be 30 inches times 13.6, which is 410 inches, or about 34 feet. It would therefore be impossible to build a water barometer in a classroom; we would need the height of a 3-storey building. If the school stairwell is at least 36 feet high it would be possible to construct a water barometer by placing the water container in the basement and the barometer tube in the stairwell. However, it should be apparent that, because of its high density, mercury is a much more convenient barometric liquid than water.

Things to Remember

A *theory* is a picture or model that both explains what happens and predicts what will happen in certain circumstances.

The *kinetic theory* states: [**1**] Gas molecules move in all directions at high speeds, [**2**] The higher the temperature the faster is the speed of the molecules, [**3**] Molecules collide with each other and bounce away in different directions, [**4**] Gas pressure is caused by gas molecules hitting a surface.

The *pressure* exerted on a surface is the force acting on a unit area.

Air pressure acts in all directions.

The *pressure of the atmosphere* is equal to the pressure of a mercury column 76 centimeters (or 30 inches) high, or approximately equal to 15 pounds per square inch.

Questions

Part A

1. Explain why the smell of ammonia soon spreads to all parts of the room if the stopper is removed from a bottle of ammonium hydroxide.
2. What is meant by the word *pressure*? What is the pressure of the atmosphere?
3. Compute the barometer reading in centimeters if the height of the mercury column is 28 inches.
4. Compute the barometer reading in inches if the height of the mercury column is 79 centimeters.

Part B

5. Although gas molecules travel at high speeds it takes several minutes for ammonia molecules to pass from one end to the other of a closed tube about 3 feet long. Explain why.
6. Describe an experiment to show that the speed of gas molecules increases when the temperature of the gas is raised.
7. What is the kinetic theory?
8. Draw a mercury barometer and explain how it operates.
9. If a little air were admitted into the space above the mercury in a barometer, what would happen? Why?
10. How does the kinetic theory account for gas pressure?
11. Water can be ejected from a medicine dropper by squeezing the bulb. Explain why.
12. What is the pressure exerted on a piston whose area is 15 square inches if air exerts a force of 225 pounds on the piston?

Things to Do

1. Air Exerts Pressure

Moisten the rims of two similar rubber sink plungers. Press the plungers together tightly and then try to pull them apart. Why is it very difficult to separate the plungers?

2. Air Exerts an Upward Pressure

Completely fill a glass tumbler with water. Press a piece of thin cardboard onto the tumbler; supporting the cardboard with one hand, turn the tumbler upside down. Now remove your hand from the cardboard. The water does not fall out of the tumbler. Why not?

8

Some Properties of Liquids

Although early man tamed animals to do work he also realized that, in wind and running water, energy was offered to him as a gift of nature. All he had to do was to find a way to utilize this kinetic energy. It is not surprising to read that he invented windmills and water wheels to transform energy supplied by nature into mechanical energy. Both have been used for many centuries. The early Egyptians, for example, used water wheels for grinding wheat into flour more than 2000 years ago.

Water Wheels

The earliest water wheel was an ***undershot wheel,*** so called because the water struck the lower part of the wheel. This wheel was constructed of wood and had a rim of vanes to catch the water. It was placed in a swift-flowing stream as shown in Fig. 8-1, and was rotated by the impact of the water against the vanes. The axle of the wheel was attached to machinery by belts or gears so that the rotating axle operated a machine which, in turn, was able to do useful work.

A later model was an ***overshot wheel.*** This was a large wheel, 50 or 60 feet in diameter, with "buckets" on the rim. A large wheel of this type could only be used below a natural waterfall, or in a stream that had been dammed up. The wheel was rotated when water fell in the upper buckets on the far side of the wheel. Overshot wheels were commonly used to operate sawmills for cutting timber and to turn millstones for grinding wheat. Even now they can be seen near some old mills (see Fig. 8-2). There are relatively few of them, however, the energy of running water having been largely replaced by electricity.

A modern water wheel is a ***Pelton wheel.*** This is an undershot wheel rotated by water falling from considerable heights, heights of 1000 feet or so. The water, carried by pipes from these high elevations,

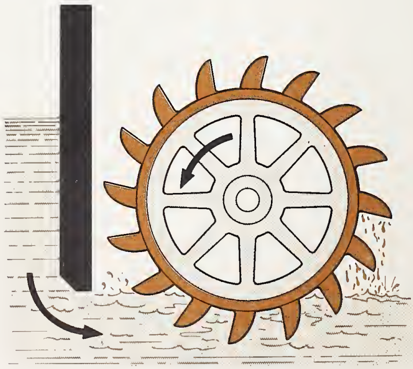

Fig. 8-1. An undershot wheel.

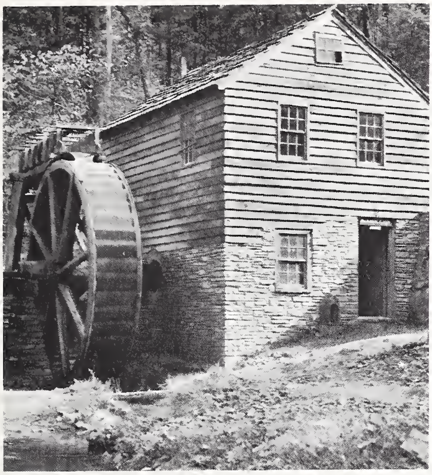

Fig. 8-2. An overshot wheel. Water is led through a wooden duct to the downward side of the large wheel.

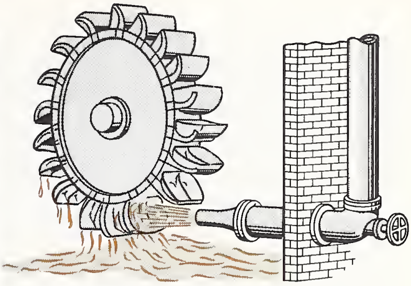

Fig. 8-3. A Pelton wheel.

shoots through a nozzle and strikes the curved blades on the rim of the wheel. The greater the height the greater is the speed of the water and, under this impact, a Pelton wheel rotates at a tremendous rate. By means of connecting belts or gears, a Pelton wheel is able to operate a wide variety of machinery.

A Water Turbine

By far the most useful water wheel is the ***water turbine***. (The word "turbine" is derived from the Latin word *turbo,* meaning "spinning-top" or "whirlwind.") Unlike other water wheels, turbines rotate with the axle vertical, not horizontal. Water is led to the turbine through a steep wide tube as shown in Fig. 8-4. The rushing water strikes the vanes and the turbine is rotated rapidly even though it is completely submerged in water. The spent water (that is, water which has lost most of its kinetic energy) then falls into a channel and is carried away.

Enormous turbines have been constructed near the foot of Niagara Falls. The water drops through a height of almost 140 feet. About 20,000 cubic feet of water pass through each turbine every minute thereby developing an output of about 5000 horsepower in each machine. This enormous power is used to generate electricity. To do this, the rotating vertical shaft of the turbine passes into a generator. A generator is a huge machine which consists of coils of wire and an enormous magnet. When the coils rotate through the field of the magnet a current is generated in the coils.

Notice again that this is an example of the transformation of energy. The potential energy of the water at the top of Niagara

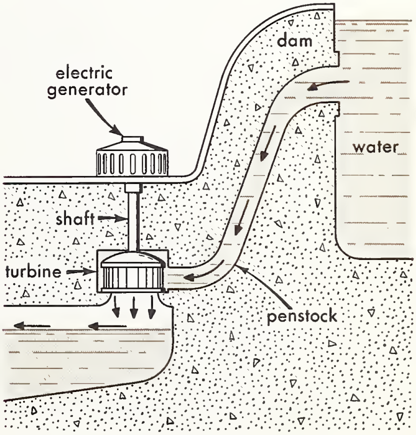

Fig. 8-4. A water turbine.

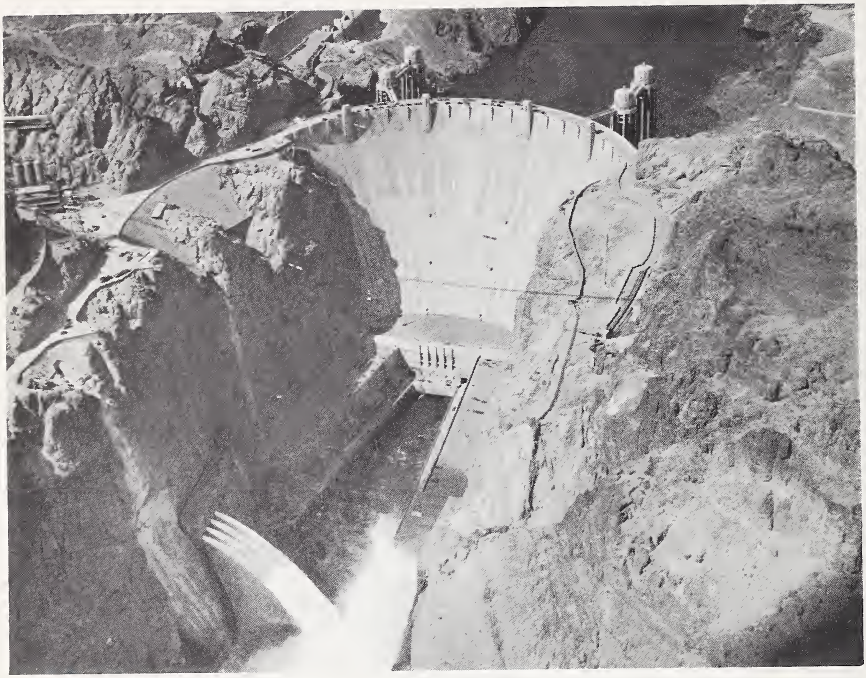

Fig. 8-5. This concrete dam holds back a lake more than 100 miles long.

Falls is changed to kinetic energy at the bottom; the kinetic energy of the water does work on the turbine; the input energy from the turbine is transfered to the generator which, in turn, changes mechanical energy to electrical energy.

Thus the energy supplied by nature is converted into electrical energy. At first sight it looks as though electrical energy should be very cheap. We must remember, however, that an enormous constructional job is involved before the large-scale transformation of potential energy of water to electrical energy can be accomplished. Some idea of the task involved is shown in Fig. 8-5. Here a 700-foot concrete wall has been built to form an artificial lake. Water from the lake flows down vertical towers, then through wide steel tubes called penstocks. From the penstocks the rushing water is led into a power plant where the turbines and generators are situated.

Pressure Exerted by Water

In the last chapter we considered the pressure exerted by a gas. Does a liquid behave like a gas or a solid in this respect? Two simple experiments will help us to answer this important question.

Experiment

8-1. To show that the pressure of water increases with depth

Punch three holes, one below the other, in a large tin can. The uppermost hole should be about one-third of the way down,

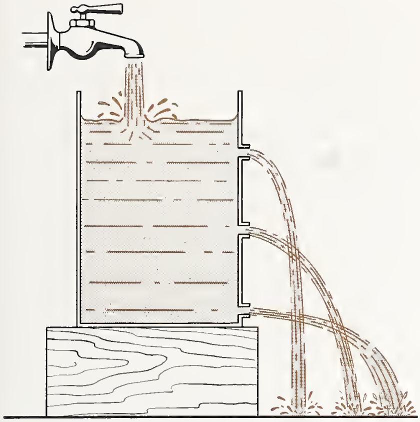

Fig. 8-6. The curvature of the streams indicates that pressure of water increases with depth.

and the lowest hole should be near the bottom of the can as shown in Fig. 8-6.

Fill the can from a faucet and let enough water run into the can to keep it filled. Notice the curvature of the streams that come out of each of the holes. Which stream indicates the greatest pressure?

The lowest stream shoots out the farthest and is therefore being forced out with the greatest pressure. The highest stream shoots out the least horizontal distance and is therefore being forced out with the least pressure.

From our experiment we would conclude that ***the pressure in a liquid increases as the depth (or height) increases***. But this is precisely what we found for a gas in the last chapter, when we learned that atmospheric pressure was greater at sea level than on top of a mountain. Does it also apply to solids? Let us consider a cubic block of copper the sides of which are 10 centimeters. The volume of the block is 1000 cubic centimeters (why?) and its weight is about 9000 grams. The area of its base is 100 square centimeters (why?) and therefore the pressure exerted on the table on which the block is resting is $\frac{9000}{100}$, or 90 grams per square centimeter.

Let us now take another block of copper, with a length of 5 centimeters, breadth of 10 centimeters, and height of 20 centimeters (see Fig. 8-7). The volume of the block is 5 times 10 times 20, or 1000 cubic centimeters, precisely the same as the other. Therefore the weights of the two blocks are alike, namely 9000 grams. What is the downward pressure exerted by

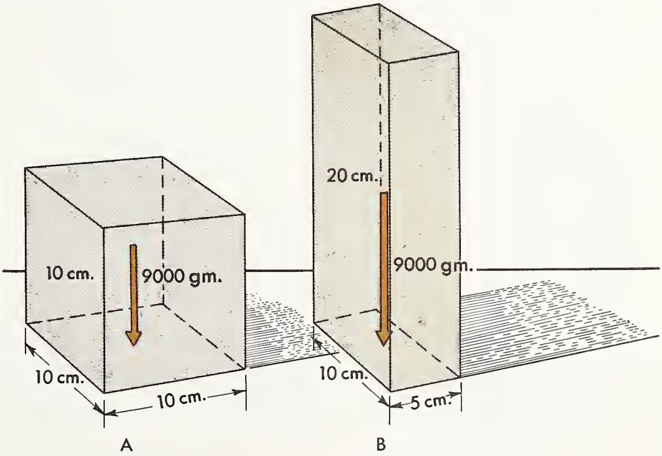

Fig. 8-7. The pressure exerted by A is twice the pressure exerted by B.

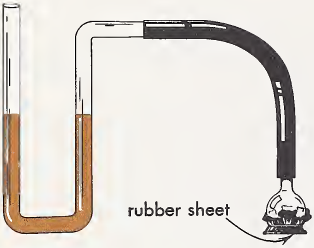

Fig. 8-8. A manometer.

the second block? The area of the base of the second block is 50 square centimeters (5 times 10) and therefore the pressure is $\frac{9000}{50}$, or 180 grams per square centimeter. Hence, by doubling the height of the block, the pressure exerted on the table has been doubled. Therefore, we conclude that for a solid, as well as for a liquid, the pressure increases as the height increases.

Transmission of Pressure by Liquids

We noticed that the streams of water leaving the can were thrust out sideways. It looks as though water exerts a sideways pressure as well as a downward pressure. Let us examine this a little more closely.

We can also examine pressure in a liquid by stretching a rubber sheet over the mouth of a short thistle tube. To do this we hold the stretched sheet in place by rubber bands or thread, and then attach the stem of the thistle tube to a manometer by a piece of rubber tubing. The arrangement is shown in Fig. 8-8. A manometer is simply a U-shaped glass tube about half full of colored water.

If the finger is pressed lightly against the stretched rubber sheet, the water level on the near side of the U-tube immediately falls. Why? The pressure exerted on the rubber is transferred to air molecules above the water column because by depressing the sheet, these air molecules are confined within a smaller space. Hence, the rate of bombardment of the water surface is increased. This constitutes an increase in pressure which pushes the water column down.

Experiment

8-2. To show that pressure in a liquid is transmitted in all directions

Lower the thistle tube into a battery jar containing water. Notice that the water column falls on the near side of the manometer. Is this what you expect? Why? Now hold the thistle tube at the same depth near the bottom of the jar, but turn it sideways in all directions. Notice that the water levels in the manometer remain the same whichever way the thistle tube is turned. What does this indicate?

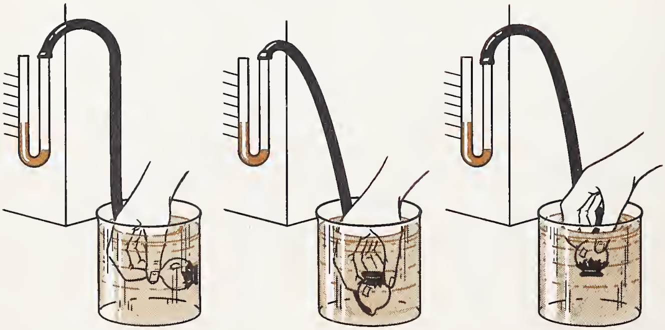

Fig. 8-9. Pressure in a liquid is transmitted in all directions.

The experiment clearly indicates that the pressure exerted by a column of water is exerted in all directions. How is this possible? The molecules of a liquid are free to move. Indeed they slide past each other so easily that a liquid is unable to keep a particular shape. And for this reason a liquid must be contained in a vessel. *Since molecules in liquids can move in all directions, pressure in liquids is transmitted in all directions*. Thus, in the tin-can experiment, the weight of the water column is not only exerted downward but in all other directions as well. And that is why the water is forced out through the holes in the side.

In this respect a liquid behaves quite differently from a solid. The particles of a solid are not free to move (that is why it is a solid) and so they are unable to exert a sideways pressure.

The Pressure Exerted by Deep Water

Because pressure increases with depth, a man cannot go very far below the surface of the water. Even a deep-sea diver in a special suit can only go down about 300 feet. The normal limit for a submarine is also about 300 feet although some of the modern ones have cruised at depths of 800 and 900 feet. At these depths the water pressure is enormous, and if submarines were not carefully designed and their hulls not made very strong, they would be crushed and buckled like the tin can described on page 67.

It should now be apparent that the water pressure exerted against a concrete dam depends upon the depth of the water in the lake, but not on the size of the lake. For example, Hoover Dam, in the state of Colorado, holds back the waters of an artificial lake which is 115 miles long (see Fig. 8-5). But the force tending to burst the dam has nothing to do with the length or area of the lake. It depends only upon the pressure and this, as you recall, increases with the depth of water. A dam is therefore constructed with this in mind. The Hoover Dam is only 45 feet thick at the top but, at the bottom, the concrete is 600 feet thick. This enormous pile of concrete is more massive than the Great Pyramid in Egypt we referred to in Chapter 2.

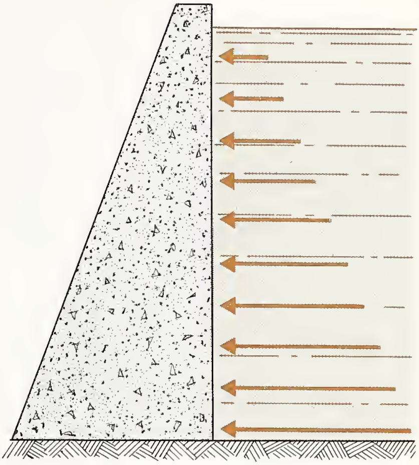

Fig. 8-10. A concrete dam is much thicker at the bottom than at the top. The increasing lengths of the arrows show how pressure increases with depth.

A Hydraulic Press

There are numerous familiar examples of transmission of pressure in confined liquids. Hydraulic brakes, barbers' chairs, automobile lifts in service stations, hydraulic presses—all these depend on the ability of liquids to transmit pressure. A hydraulic press is one of the most efficient of all machines. Let us see how it operates.

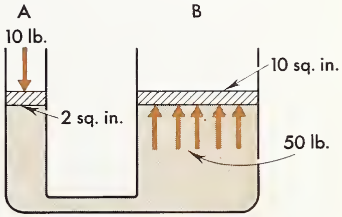

Fig. 8-11. The mechanical advantage of this hydraulic press is 5.

A hydraulic press consists of two cylinders A and B (see Fig. 8-11), connected by a tube. The cylinders and tube are filled with water (or preferably oil) and tightly fitting pistons are then inserted in the cylinders. Suppose the area of A is 2 square inches and the area of B is 10 square inches. Suppose also that we exert a force of 10 pounds on piston A. What happens to piston B? The pressure on piston A is 5 pounds per square inch $\left(\frac{\text{10 pounds}}{\text{2 square inches}}\right)$ and this pressure is transmitted through the water in all directions. Therefore an upward pressure of 5 pounds per square inch is exerted on piston B. And since the area of this piston is 10 square inches the upward *force* exerted by piston B is 50 pounds (5 lb./sq. in × 10 sq. in.).

Here then is a device for multiplying force. What is its mechanical advantage? Mechanical advantage =

$$\frac{\text{output force}}{\text{input force}} = \frac{\text{50 pounds}}{\text{10 pounds}} = 5.$$

Notice also that this ratio (5/1) is the same as the ratio of the areas of the pistons (10 sq. in./2 sq. in). Therefore, we can say that the mechanical advantage =

$$\frac{\text{output force}}{\text{input force}} = \frac{\text{area of output piston}}{\text{area of input piston}}$$

It is apparent that a hydraulic press (or any machine that operates on the same principle) can give an enormous mechanical advantage. For instance, if the area of the large piston is 100 times the area of the small piston the mechanical advantage of the press is 100. We must remember, however, that what is gained in force is lost in speed (or distance).

If piston A is pushed down 5 inches, the volume of water in cylinder A is decreased by 10 cubic inches (5 inches times 2 square inches). Where does this water go? It flows into cylinder B, and therefore piston B is pushed up far enough to make room for these 10 cubic inches of water that are displaced. How far will piston B rise? The area of piston B is 10 square

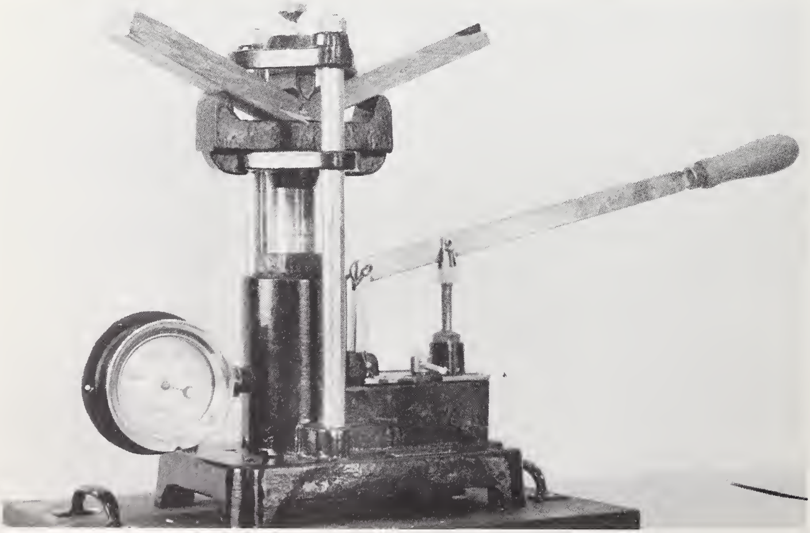

Fig. 8-12. A hydraulic press, laboratory model.

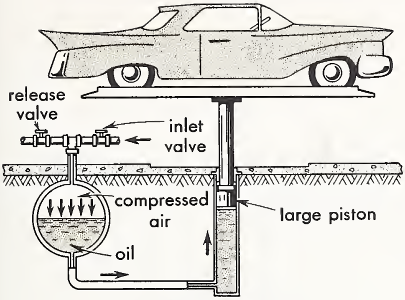

Fig. 8-13. An automobile in a service station is lifted by a hydraulic press.

inches and therefore it rises only one inch $\left(\frac{10 \text{ cu. in.}}{10 \text{ sq. in.}} = 1 \text{ in.}\right)$. In other words, the force exerted by piston A is one-fifth the force exerted by piston B, but the distance moved by piston A is 5 times as great as the distance moved by piston B.

A Laboratory Model of a Hydraulic Press

In the model shown in Fig. 8-12 a small force applied at the end of the lever arm is multiplied into a crushing force large enough to break a thick piece of wood. This device is a combination of two machines, a lever and a hydraulic press, each with its own mechanical advantage. The effort is first multiplied by the lever, and the output force from the lever is passed on to the small piston of the press. The pressure is then transmitted through oil (not water) to the large piston, thereby multiplying the force a second time. If, for example, the mechanical advantage of the lever is 10 and the mechanical advantage of the press is 20, the mechanical advantage of the system is 200. No wonder it is possible to break a stout board by exerting a relatively small force.

In a service station, as you have no doubt observed, automobiles weighing more than a ton are lifted by a hydraulic press, the effort usually being supplied by com-

Fig. 8-14. A large hydraulic press shaping automobile tops out of sheet steel.

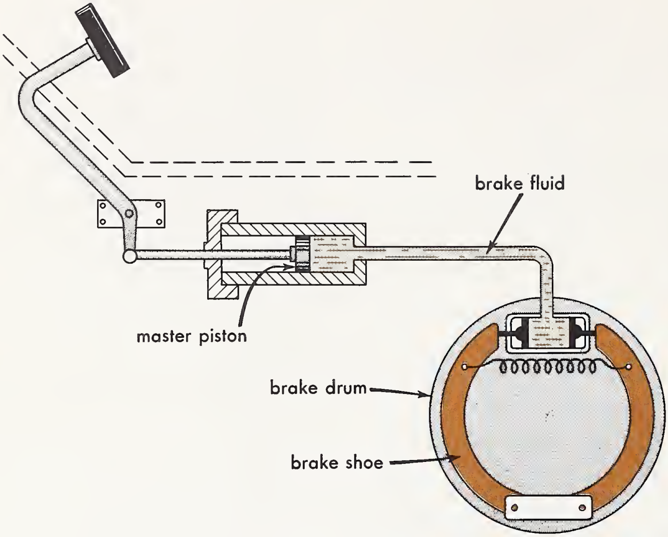

Fig. 8-15. Hydraulic automobile brakes.

pressed air. Still another hydraulic press put to industrial use is that shown in Fig. 8-14. This gigantic press is used to shape the tops of automobiles out of a flat sheet of steel. The machine exerts such a large force that the whole roof of the automobile is shaped in one operation.

Hydraulic Brakes

The operation of hydraulic brakes on an automobile also depends on the transmission of pressure. When the driver of the car steps on the brake pedal, a master piston pushes against the surface of oil in a cylinder (see Fig. 8-15). The oil transmits the applied pressure to a brake cylinder and piston on each wheel of the automobile. The wheel pistons then push the brake shoe against a drum on each of the wheels, and the force of friction stops the automobile. When the foot is taken off the pedal, force is no longer transmitted through the oil and the brake shoe is pulled away from the drum by a spring.

Solids, Liquids, and Gases

Having discussed some of the properties of gases and liquids it may be well to summarize the differences between solids, liquids, and gases. We are familiar with the fact that, depending on conditions, a given substance may exist as a solid or a liquid or a gas. These conditions in which matter can exist are called ***states of matter***. Thus, if water is cooled sufficiently it changes to ice (a solid) and if it is heated it changes to water vapor (a gas). This change in the states of matter can easily be shown by heating some sulphur in a test tube.

Experiment

8-3. To change sulphur from a solid to a liquid to a gas

Place some sulphur, about half an inch deep, into a dry test tube. Hold the test tube by a clamp and heat the sulphur *gently* in the hot gases above a small Bunsen flame, rotating the test tube as it is being heated. Observe that the sulphur melts to form a yellow liquid. If this liquid is heated more strongly, it darkens in color and boils. Sulphur vapor (or gas) escapes during the boiling and some of it condenses to a yellow powder on the upper, cool part of the test tube.

How can we account for these various states of matter? Sulphur crystals (or sulphur solid) are made up of molecules that stick to each other. That is to say, the molecules must be attracted to each other by strong forces. The heat from the Bunsen burner supplies enough energy to break the bonds between the sulphur molecules. When this happens the sulphur molecules can move around freely and we say the sulphur has melted. If the heating is increased, the molecules gain kinetic energy and their speeds increase. These fast-moving molecules are then able to escape from the liquid and enter the air. We then say that the sulphur has changed to a gas (or vapor). If the gas molecules strike a cold part of the test tube their speeds are slowed down, the attractive forces again cause the molecules to stick together and we say that a solid is formed.

Solids

What, then, are solids? Because of the closeness of the molecules (or atoms) and the strong forces between them, solids are rigid bodies, with a definite shape and size.

Liquids

The forces of attraction between molecules of a liquid are weaker than the forces between molecules (or atoms) of a solid. As a result, the molecules of a liquid are free to move; they are constantly shifting and turning. Because of this property, a pressure applied to a liquid is transmitted to all parts of it. But although the molecules of a liquid are free to move, they are close together, and, as a result, liquids are almost incompressible. In other words, the volume of a liquid is not appreciably diminished even if it is subjected to extremely great pressures.

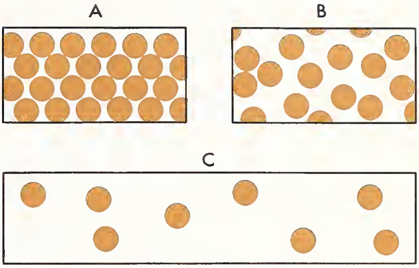

Fig. 8-16.

A represents a solid.

B represents a liquid.

C represents a gas.

Each circle represents a molecule.

Notice that the gas molecules in C occupy only a small part of the enclosed space.

Because the molecules are free to move, a liquid needs a container to keep it in place. But it readily changes shape when poured from one vessel to another. In this respect, a liquid differs markedly from a solid. However, although a liquid changes its shape it does not change its size (or volume).

Gases

A gas differs from a solid or a liquid because it readily changes *both* its size and shape. Why is this? The molecules of a gas are relatively far apart so that there is little attraction between them. They move about freely in all directions and always "fill" their container. But bear in mind that the word "fill" simply means that the molecules move freely to all parts of the container. Because the molecules are far apart (see Fig. 8-16), a gas is easily compressed. That is to say, the volume of the air in a bicycle pump can be diminished a great deal by pushing on the handle. What is meant by reducing the volume of a gas? When the piston moves down the cylinder of a bicycle pump, the molecules are pushed closer together; the spaces between the molecules are diminished, but the molecules themselves are not affected. The sizes of individual molecules are not changed no matter how large a pressure is applied to the gas.

Things to Remember

Water wheels transform the kinetic energy of running water into mechanical energy.

A *water turbine* is the most useful form of water wheel.

The *pressure in a liquid* increases as the depth increases.

Pressure in liquids is transmitted in all directions.

Mechanical advantage of a hydraulic press equals $\dfrac{\text{area of output piston}}{\text{area of input piston}}$.

A *solid* has a fixed size and shape; a *liquid* has a fixed size but not a fixed shape; a *gas* has neither a fixed size nor a fixed shape.

Questions

Part A

1. What is [**a**] an undershot wheel, [**b**] an overshot wheel?
2. What is a Pelton wheel and how does it operate?
3. What is the essential difference between a water wheel used as a machine and a pulley or lever?
4. A concrete dam is much thicker at the bottom than at the top. Explain why.
5. What is a manometer?
6. What is a hydraulic press?
7. The area of the small piston of a hydraulic press is 10 square inches and the mechanical advantage of the press is 20. What is the area of the large piston?
8. If the large piston in Question 7 moves up 1 inch, how far down does the small piston move?
9. What is [**a**] a solid, [**b**] a liquid, [**c**] a gas?

Part B

10. Explain how water, falling in an overshot wheel, causes the wheel to rotate.
11. Discuss the various energy changes that occur in a turbine-generator combination.
12. Describe an experiment to show that water pressure increases with the depth of water.
13. Describe an experiment to show that pressure in water is transmitted in all directions.
14. How does the kinetic theory account for the transmission of pressure in water?

15. Explain why the mechanical advantage of a hydraulic press equals $\frac{\text{area of large piston}}{\text{area of small piston}}$.
16. If the effort were applied to the large piston of a hydraulic press, would its mechanical advantage be greater or less than one? Why?
17. Explain how the hydraulic brakes on an automobile operate.
18. Why is a solid a solid?
19. Explain clearly what happens when a gas is compressed.
20. What is the main difference between a liquid and a gas?

Things to Do

To Show the Upward Pressure of Water

Coat a cardboard tube, about a foot long, with shellac to make it water resistant. (A glass cylinder will serve even better than a cardboard tube.) Then cut a square of cardboard about 2 inches on each side and coat it with shellac. Attach one end of a piece of thread (about 18 inches long) to the center of the cardboard by means of tape. Put the other end of the thread through the tube and then pull the thread so that the cardboard fits snugly on the bottom of the tube. Holding the cardboard in place, lower the tube into a bucket or battery jar containing water. Release the thread and observe that the cardboard does not fall. Why not? Now pour water into the tube (if the water is colored with red ink it can be seen better) until the cardboard falls away from this tube. What is the height of the water in the tube when this happens?

You will notice that the cardboard falls when the water level in the tube is the same as the level outside. Can you explain why?

9

Water Pumps and Buoyancy

If one end of a steel pipe is held under water, the levels of the water inside and outside the pipe will be the same. Why? How could we make water rise up the pipe? Air would have to be removed from the pipe. If all the air were removed from the pipe, how high would the water rise? The answer is, of course, 34 feet. A device that removes air from a pipe, thereby enabling water to flow continuously up the pipe, is called a *pump*.

A Lift Pump

The operation of a pump depends upon atmospheric pressure and the transmission of this pressure through water. The particular kind of pump called a ***lift pump*** consists of a long tube with a short cylinder at the top of it. At the bottom of the cylinder there is an inlet valve, usually a flap of leather which allows upflowing water to pass through, but prevents water from returning down the pipe. A piston, operated by the pump handle, moves up and down in the cylinder. The piston has a hole through it. This hole is covered by an outlet valve which allows water to pass through in an upward direction. The piston and valves in the pump cylinder are shown in Fig. 9-1.

To remove air from the pipe, the handle is pushed *down,* thereby forcing the piston *up* the cylinder. This reduces the air pressure in the tube and cylinder (why?), and, as a result atmospheric pressure on the outside water surface forces some water up the tube. When the handle is raised, the piston moves down. This movement of the piston forces some air in the cylinder through the outlet valve. Why is this? After several strokes of the handle, water fills the pipe, passes through the inlet or lower valve and into the cylinder. On the next downstroke of the handle, water in the cylinder is lifted by the piston and leaves the pump through the spout.

The piston does not make an airtight connection with the cylinder wall; therefore the pump is unable to create a perfect vacuum above the water column. As a result, water cannot be lifted to a height of 34 feet. In practice, it is found that the maximum height water can be raised by a lift pump is about 28 feet.

A Force Pump

If water has to be raised more than 28 feet, atmospheric pressure is not enough and an additional pressure must be applied to the water. A device that enables us to do this is a ***force pump***. The main difference between a lift pump and a force pump is the way the piston operates. The piston of a lift pump has a hole through it, but there is no hole through the piston of a force pump. Moreover, the outlet

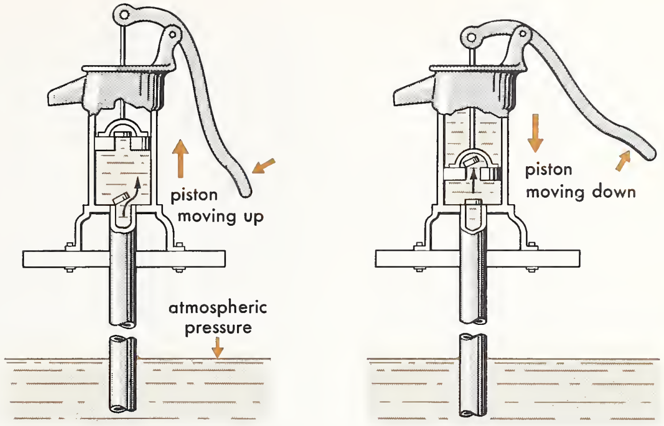

Fig. 9-1. A lift pump.

valve of a force pump is on the side of the cylinder as shown in Fig. 9-2.

As the piston of a force pump is moved up and down, atmospheric pressure lifts water through the pipe and into the cylinder exactly as in a lift pump. This situation is shown in Fig. 9-2. What happens at the next downstroke? The piston closes the inlet valve (why?), forces water through the outlet valve and up the outlet pipe. Notice that water is forced up the outlet pipe by pressure applied to the piston, not by atmospheric pressure. Water, therefore, leaves the nozzle of the outlet pipe on the downstroke of the piston but not on the upstroke.

It would be an advantage to have a continuous stream of water through the nozzle rather than a stream that keeps stopping and starting (an intermittent stream). To do this, an air dome is usually placed in the outlet pipe. How does this operate? On the downstroke of the piston (see Fig. 9-2) some water is forced into the dome, thereby trapping and compressing the air in the dome. On the next upstroke, pressure is not applied by the piston. Instead, the pressure exerted by the compressed air in the dome forces more water through the nozzle. That is to say, water is expelled through the nozzle on both the down-

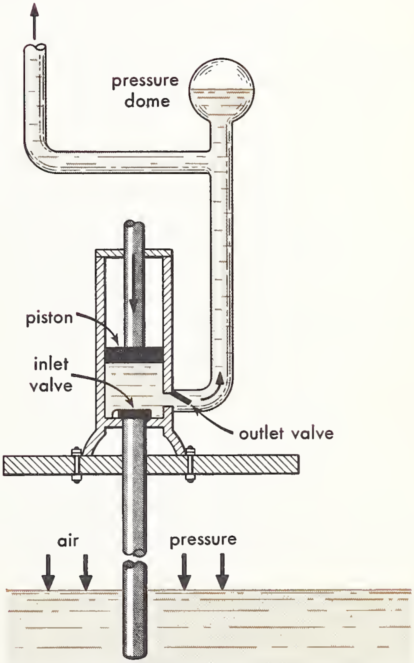

Fig. 9-2. A force pump.

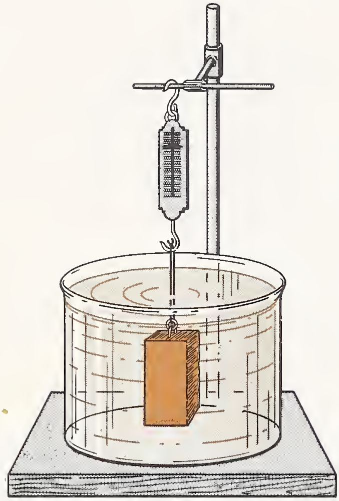

Fig. 9-3. The brick appears to lose weight when immersed in water.

stroke and upstroke of the piston; in other words in a continuous stream.

Buoyancy

It is the common experience of swimmers that they appear to lose weight in water. Indeed, when they are floating they appear to have no weight at all! How can this be explained? First let us show that the weight of a body, as registered by a spring balance, is less in water than in air.

Experiment

9-1. To compare the weight of a body in air with its weight in water

Tie a string around a brick and suspend the brick from a spring balance. Note its weight. Slowly lower the brick into water in a battery jar and observe the reading of the spring balance. You will notice that the brick gradually loses weight until it is submerged. No further change in weight then takes place no matter how far the brick is submerged.

We can account for this apparent loss in weight only by assuming that an upward force buoys up the brick when it is immersed in water. Or, we can say that ***water exerts a buoyant force upon any object immersed in it.*** What causes the buoyant force and how can it be measured?

When a body is submerged in water it is acted upon by pressures from all directions–from above, from below, and from the sides. The side pressures come from opposite directions at all levels. These side pressures counteract each other; otherwise, an immersed body would move sideways. But the vertical pressures do not counteract each other. The upward pressure on the lower surface is greater than the downward pressure on the upper surface. Why? The difference between the upward and downward forces is called ***buoyancy*** (or buoyant force). Let us find the buoyant force on a body.

Experiment

9-2. To find the buoyant force on an object that sinks in water

Measure the edges of a brick in centimeters and compute its volume. Suspend the brick from a spring balance and read its weight in grams. Lower the brick into water in a battery jar until it is completely immersed. Again read the spring balance and find the loss in weight of the brick. The volume of the water displaced is the volume of the brick. Moreover, the number representing the volume of the water displaced in cubic centimeters is the same as the number representing the weight of the water displaced in grams. What is the weight of the water displaced? How does this compare with the apparent loss in weight of the brick?

Notice that the buoyant force is precisely the same as the weight of the water displaced. This is an important observation. It has been known for centuries; it was first stated by Archimedes about 200 B.C. and is called Archimedes' principle. Archi-

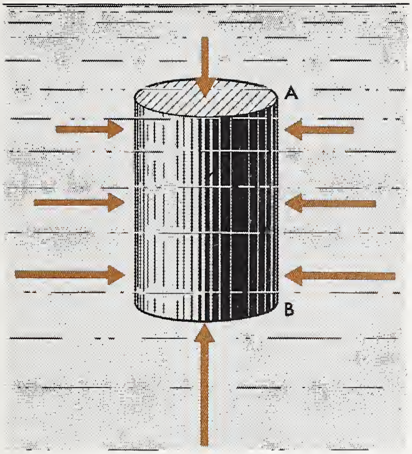

Fig. 9-4. When a body is immersed in water, the side pressures counteract each other, but the upward pressure on surface B is greater than the downward pressure on surface A.

medes' principle can be stated as *any object immersed in water is buoyed up by a force equal to the weight of the water displaced.*

Floating Bodies

Does Archimedes' principle apply to floating bodies? We are certainly aware of a buoyant force when we float in water. The density of the human body is a little bit less than the density of water and that is why it can be completely supported by the buoyancy of the water.

Experiment

9-3. To verify Archimedes' principle for a floating body

A suitable floating body is a small can half-filled with water. Weigh the can and water. Then gently lower it into an overflow can, filled with water, until the bucket floats (see Fig. 9-5). Collect the displaced water in a beaker and weigh it. Compare the weight of the catch bucket and its contents with the weight of the displaced water. What is your conclusion?

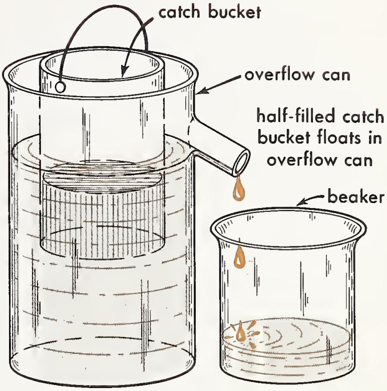

Fig. 9-5. A floating body displaces its own weight of water.

The data should certainly support the statement that *a floating body displaces its own weight of water.* In other words, Archimedes' principle applies both to floating and submerged bodies. That is to say, a more general statement of Archimedes' principle is *any object wholly or partly immersed in a liquid is buoyed up by a force equal to the weight of the liquid displaced.*

A floating piece of wood is a familiar sight. The wood floats part in and part out of water. Can we compute what fraction of the wood will be below the water line? Suppose we have a cubic block of wood the volume of which is 200 cubic centimeters and the weight of which is 150 grams. If the wood is placed in water it will displace 150 grams of water. Why? Therefore the wood displaces 150 cubic centimeters of water. Hence, when the wood floats, three-quarters of it is under water and one-quarter is out of water.

Why a Ship Floats

Long before Archimedes stated his principle of buoyancy, early man learned by experience that a hollowed-out tree trunk would float even if it carried a load. Hollowed-out tree trunks were the earliest boats. But it took many centuries for man to learn that iron could be made to float as well as wood. All he had to do was to increase the buoyancy; that is, to decrease the weight by "hollowing it out." The iron must be shaped into a shell so that it displaces a very large quantity of water. A steel ship is built this way. It was not until 1780 that the first steel ship was launched.

What determines how much cargo a ship can carry? If a ship weighs 5000 tons, and if it can displace 15,000 tons of water without sinking, the ship can carry a cargo of 10,000 tons. Why? But, as you know, a ship of this size is relatively small. Some ships have a tonnage of 50,000 tons or even more. A 25,000-ton ship is designed to displace 25,000 tons of water (see Fig. 9-6).

Fig. 9-6. A 25,000-ton ship displaces 25,000 tons of water.

A Submarine

The question of buoyancy is very important in operating a submarine. A submarine normally floats with about one-quarter of its volume out of water. To submerge the submarine it must be made heavier. How can this be done? A submarine has large tanks which can be filled with sea water. As the tanks are being filled, horizontal diving planes, like the wings on an airplane, are used to make it glide downward, and to control the depth to which it will submerge. To bring a submarine to the surface it must be made lighter. To do this, compressed air forces water out of the tanks and, at the same time, the diving planes are set so that the bow of the boat is pushed upward.

Things to Remember

A *lift pump* can raise water about 28 feet.

A *force pump* can raise water considerably more than 28 feet.

Water exerts a *buoyant force* upon any object immersed in it.

Archimedes' principle states: Any object wholly or partly immersed in a liquid is buoyed up by a force equal to the weight of the liquid displaced.

Questions

Part A

1. What is a pump?
2. What is the maximum height water can be raised in a lift pump? Why?
3. What is the purpose of the handle of a lift pump?
4. What is a force pump?
5. Why is the piston of a force pump solid and without a hole as in a lift pump?
6. What is the advantage of an air dome in a force pump?
7. Why does an object appear to lose weight when immersed in water?

8. Why does a piece of wood float and not sink?
9. State Archimedes' principle.
10. A lump of iron sinks in water. But if this lump of iron is melted and cast into a thin hemispherical shell it will float. Explain why.
11. What is the meaning of the phrase "a 20,000-ton ship"?

Part B

12. Draw a diagram of the cylinder, piston, and valves of a lift pump. Explain how the valves operate.
13. Draw a diagram of the cylinder, piston, and valves of a force pump, and explain how the valves operate.
14. Draw a diagram of a section of a force pump that includes the air dome, and explain how the air dome operates.
15. Describe an experiment which verifies Archimedes' principle as applied to a floating body.
16. The volume of a block of wood is 250 grams and its weight is 200 grams. What fraction of the wood will be above water when it floats?
17. How is a submarine submerged and how is a submerged submarine brought to the surface?

Things to Do

1. Why is it easier to float in salt water than in fresh water?

Put an egg into a tall liter beaker and then pour water into the beaker until it is about one-third full. The egg remains at the bottom of the beaker. Make a saturated salt solution in another beaker. Put the egg in this solution and notice that it floats. Why does it sink in fresh water and float in a concentrated solution of salt?

2. To make a diver

Almost fill a wide-mouthed glass jar with water. Half fill a small test tube, about 2 inches long, with water. (A vial can be used instead.) Close the tube with the finger, invert the tube, place the open end under water and remove the finger. The tube should float only about one-quarter inch above water. If more than this is above water, take the tube out, pour a little more water in the tube, and then float it again. Repeat the adjustments until the tube floats with only a little of it above water. Stretch a piece of sheet rubber over the mouth of the jar (a piece of an old inner tube will do) and hold it in place with a rubber band (or tie it in place with thread).

Now press on the stretched rubber with the finger and the diver sinks to the bottom of the jar. Release the pressure and the diver rises to the surface. The diver can be made to rise and sink indefinitely. How can you explain it?

UNIT
III
Combustion and Fuels

10

Oxygen and Hydrogen

In earlier chapters we have referred to molecules of air and to air pressure. What are air molecules? Or, expressed another way, what is air made of? An experiment on the rusting of steel (or iron) will help us to answer this question.

Experiment

10-1. The rusting of iron

Wet some steel wool with water and place it in a flask. Close the flask with a stopper into which a glass tube (about 2 feet long) is fitted. Lower the open end into water in a beaker and support the flask by a ring and stand as shown in Fig. 10-1.

Notice that the water slowly rises up the tube. Eventually, after several hours, the water stops rising. At this point some water has entered the flask and it looks as though about one-fifth of the available space is filled with water.

How can we explain what has happened? Since water rises up the tube it looks as though the air pressure in the flask has been reduced. How is this possible? Air contains oxygen, and oxygen combines chemically with the iron (steel is about 90 per cent iron) to form a solid called iron oxide (or rust). But if oxygen gas is removed from the flask, why does the water not rise to fill the flask? This is because air also contains a gas called nitrogen and the nitrogen does not combine chemically

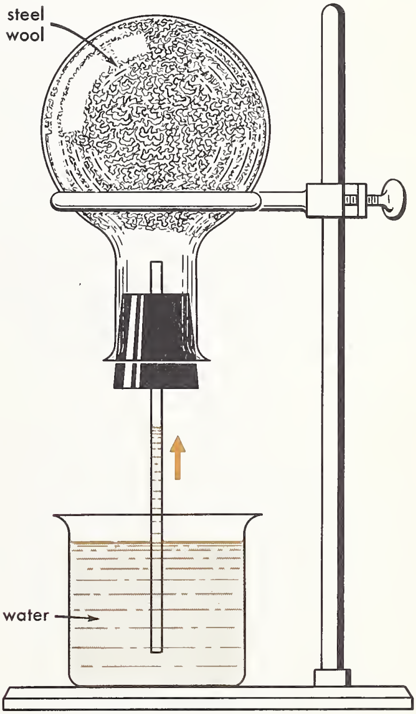

Fig. 10-1. Water rises in the tube to replace the oxygen which combines with the iron.

with the iron. We can say that air is a mixture of oxygen and nitrogen; the oxygen combines with the iron, and therefore the pressure in the flask is diminished so that atmospheric pressure is able to force water up the tube.

The Composition of Air

The above experiment shows that air is about one-fifth oxygen and four-fifths nitrogen. Actually, it is 21 per cent oxygen and 78 per cent nitrogen. Notice that oxygen and nitrogen make up 99 per cent of the air; the remaining 1 per cent consists of carbon dioxide and other gases that we shall refer to later.

We now want to examine oxygen gas and to do some experiments with it. How can it be prepared? Of course, if we could take nitrogen out of the air, we would have oxygen left. But this is easier said than done. Oxygen and nitrogen *can* be separated. But to do so we would first have to cool the air to a very low temperature and liquefy it. Liquid oxygen could then be separated from liquid nitrogen. But this is an elaborate and expensive method of preparing oxygen and not suitable as a classroom preparation. A much simpler way of preparing oxygen is to heat and decompose a compound called potassium chlorate. What, then, is a compound?

Elements and Compounds

We have stated that oxygen and nitrogen are present in air in large amounts, and carbon dioxide in very small amounts. Oxygen and nitrogen are elements; carbon dioxide is a compound.

An element is a substance that cannot be decomposed into simpler substances. Elements may be solids like carbon, copper, or iron; or liquids like mercury; or gases like oxygen and nitrogen.

Compounds, on the other hand, are made up of at least two elements. ***Compounds are formed whenever two or more elements combine with each other chemically.*** Carbon dioxide is a compound. Even its name suggests that the elements carbon and oxygen have combined to form this compound. Water is another compound—by far the most plentiful one. It is a compound of the elements hydrogen and oxygen and is sometimes called hydrogen oxide. Potassium chlorate is also a compound. It is a white solid that decomposes, releasing oxygen, when it is heated.

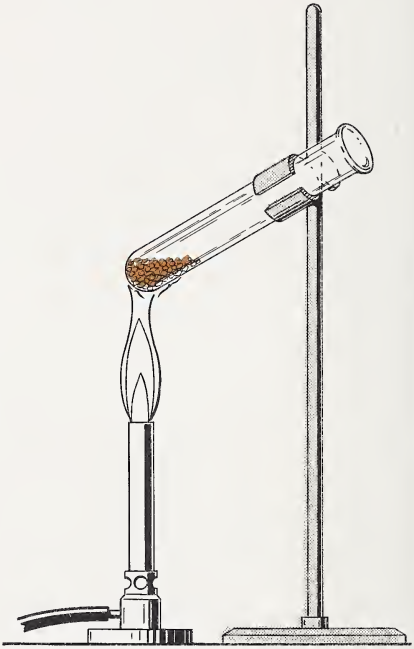

Fig. 10-2. Oxygen is released by heating potassium chlorate in a test tube.

Experiment

10-2. To test for oxygen

Place some potassium chlorate, about half an inch deep, in a test tube. Clamp the test tube to a stand, as shown in Fig. 10-2 and then heat it gently. The potassium chlorate melts and, on further heating, gas bubbles escape. When this happens, hold a glowing wooden splinter in the tube and notice that it bursts into flame. Now heat strongly until no more oxygen bubbles escape. The white residue left in the test tube is potassium chloride.

There are several important things to be learned from this experiment. The first is that ***oxygen supports burning***. The glowing splinter of wood bursts into flame because it is surrounded by oxygen and the wood reacts chemically with the oxygen. If there were no oxygen in the air, burning would be impossible.

The next thing to notice is that ***the relighting of a glowing splinter is a chemical test for oxygen***. Of course, the oxygen in the air will not relight a splinter. Why not? Air contains nitrogen, and nitrogen slows down the chemical activity of the oxygen. In other words, the splinter test is a test for pure oxygen, not for oxygen in the air.

Potassium chlorate is a compound easily decomposed by heat. The residue is potassium chloride, a compound that is not easily decomposed by heat. How do we know this? The name potassium chloride suggests that it is a compound of the elements potassium and chlorine. Therefore, potassium chlorate must be a compound of the three elements potassium, chlorine, and oxygen. How do we know this?

The decomposition of potassium chlorate is a chemical reaction. This reaction can be written as a single statement or, as we usually say, as a word equation:

potassium chlorate → potassium chloride + oxygen

Notice that we usually write an arrow to separate the starting substance (or substances) from the substances that are formed in the reaction. When we read an equation we substitute the word "yields" for the arrow. Thus we read the above equation as "Potassium chlorate yields potassium chloride plus oxygen."

A Catalyst

You probably noticed that the potassium chlorate had to be heated very strongly to drive off all the oxygen. Is it possible to decompose the potassium chlorate at a lower temperature? This would clearly be an advantage; it would save both time and fuel. The following experiment will help us to answer this question.

Experiment

10-3. To show that manganese dioxide aids the decomposition of potassium chlorate

Again put potassium chlorate, about half an inch deep, in a test tube. Heat the tube cautiously until the potassium chlorate has just melted. Hold a glowing splinter in the test tube to show that no oxygen is being evolved. Now drop a little of the black powder, manganese dioxide, into the molten chlorate. A vigorous reaction takes place immediately. Again place the glowing splinter in the test tube and notice that, this time, the splinter bursts into flame.

We can conclude from this experiment that the decomposition of potassium chlorate can be speeded up by adding a little manganese dioxide. In this reaction, the manganese dioxide is a ***catalyst. A catalyst is a substance that speeds up a chemical reaction***. The manganese dioxide is not decomposed in this reaction. We could prove this by separating it from the potassium chloride which is formed when potassium chlorate decomposes.

As we study chemistry we shall find that many different catalysts are used to speed up reactions. And, as in the case of manganese dioxide, no catalyst is ever permanently changed in a reaction. In some way, a catalyst stimulates a reaction without itself being decomposed.

To Collect a Gas

If we wish to discover the properties of a gas, we must first collect the gas in a bottle. How can this be done? Our problem is to take air out of the bottle and then put the gas into it. The simplest way to get air out of a bottle is to fill it with water. A glass cover is then placed over the bottle, the bottle is inverted and lowered into a trough of water as shown in Fig. 10-3. The glass cover is removed and the bottle placed on a "shelf" in the trough. In this position the bottle is ready to receive the gas.

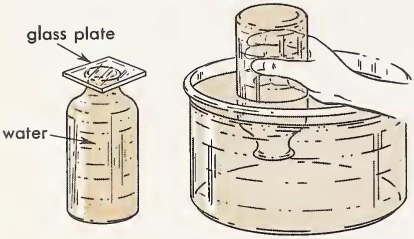

Fig. 10-3. To collect oxygen a bottle is filled with water, covered by a glass plate, and then inverted with the open end under water.

Experiment

10-4. To collect oxygen

Thoroughly mix some potassium chlorate and manganese dioxide, and then pour some of the mixture (about an inch deep) into a test tube. Place the end of a glass tube (a delivery tube) through a stopper, fit the stopper into the test tube, and arrange the apparatus as shown in Fig. 10-4.

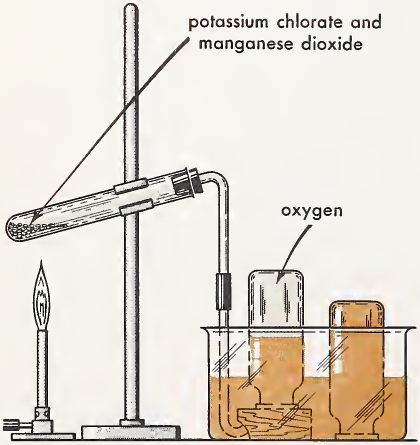

Fig. 10-4. Collecting oxygen.

Gently heat the test tube. Oxygen bubbles escape at once and collect in the bottle. When the bottle is full of oxygen, replace it by another bottle of water. This first bottle contains some air from the test tube and should be discarded. When the second bottle is filled with oxygen, slide on the glass cover while it is still under water. Keeping the cover on, lift the bottle out of the trough, and place the bottle, right side up, on the table. Collect three bottles of oxygen in this way.

Oxygen Supports Combustion

We have already stated that oxygen supports burning or combustion; this is its most important property. So far we have burned only a glowing splinter of wood in oxygen. We will now try to burn a few elements in oxygen, selecting sulphur and carbon (which are nonmetals), and magnesium (which is a metal).

Experiment

10-5. The combustion of some elements

1. *Sulphur.* Place a little powdered sulphur in a combustion spoon and lower it into a bottle of oxygen. Nothing happens. Now take the spoon out of the bottle and replace the glass cover on the bottle.

   Heat the sulphur in the flame of a Bunsen burner until it just begins to burn. Then again lower the combustion spoon into the bottle of oxygen. Notice that sulphur burns with a blue flame and that the burning is much more intense in oxygen than in air. Notice also that gas fumes are formed. Do not inhale this gas; it has an objectionable smell. The gas is sulphur dioxide.
2. *Magnesium and carbon.* Now repeat the experiment first using a few short

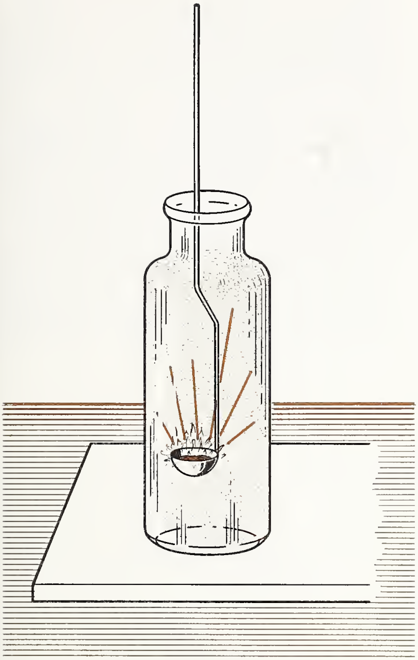

Fig. 10-5. Sulphur, in a combustion spoon, burns in a bottle of oxygen.

strips of magnesium and then a small piece of charcoal (which is a form of carbon). The magnesium will have to be heated strongly to get the burning started. As soon as the burning begins transfer the spoon to a bottle of oxygen and notice that the magnesium burns with a fierce white flame. A white powder results from this reaction; the powder is magnesium oxide.

Charcoal, too, must be strongly heated to make it glow. Glowing charcoal glows more intensely when lowered into oxygen and a gas, carbon dioxide, is formed.

Oxides

Whenever an element combines with oxygen an *oxide* is formed. That is, *an oxide is a compound of oxygen and another element.* In the above experiment the oxides formed were sulphur dioxide, magnesium oxide, and carbon dioxide. The word equations for these reactions are

sulphur + oxygen → sulphur dioxide
magnesium + oxygen → magnesium oxide
carbon + oxygen → carbon dioxide

Molecules and Atoms of Oxygen

We have observed that oxygen does not light a wooden splinter, but only a *glowing* wooden splinter. Oxygen does not combine with sulphur or carbon at ordinary temperatures either, but only with hot sulphur and hot carbon. Why is this? It is apparent that oxygen molecules are not very active at ordinary temperatures but that, if they are heated, they become chemically active. How can this be? If oxygen molecules are heated, some of them break up into ***atoms*** which are chemically very active. How is this possible? Before answering this question we must first answer the question: What is an atom? ***We can define an atom as the smallest particle of an element that can take part in a chemical reaction.***

The symbol for an atom of oxygen is O. A molecule of oxygen, however, consists of two atoms joined together by chemical bonds. We could write the symbol for a molecule of oxygen as $O{=}O$, but it is usually written as O_2, in which the subscript $_2$ indicates the number of atoms in a molecule. The effect of heat on oxygen molecules can be shown as

$$O_2 \rightarrow 2O$$

That is, if the bonds are broken, a single molecule of oxygen forms two atoms, and these exceedingly active atoms readily react with atoms of other elements. The equations for the above reactions can now be written in symbols instead of words. They are

$$\begin{aligned} S &+ O_2 \rightarrow SO_2 \\ Mg &+ O_2 \rightarrow MgO \\ C &+ O_2 \rightarrow CO_2 \end{aligned}$$

Oxidation

Oxygen combines with many elements and compounds; they are called *oxidation reactions*. In the above reactions with sulphur, carbon, and magnesium a great deal of heat is released suddenly; a flame is produced in the sulphur and magnesium reactions, and carbon becomes white hot. These are examples of *rapid oxidation*.

The rusting of iron, on the other hand, is an example of *slow oxidation*. Here the iron oxidizes slowly and although heat is released, as in all oxidation reactions, the temperature rise is very small. The slow oxidation of iron (or steel) in air raises some troublesome problems. Automobiles, bridges, and tall buildings are constructed of steel. If the steel surfaces are left exposed to the air the metal will rust and begin to distintegrate. To prevent oxidation, the exposed surfaces are painted, or even plated with a metal that does not readily rust. Steel bridges are painted but the steel bumpers on an automobile are plated with the metal chromium.

What is Oxygen Used for?

Oxidation reactions always release heat and, in many cases, a flame is produced. In a later chapter we shall read of the rapid oxidation of gasoline in an automobile engine. Here the oxidation reaction supplies the heat energy that drives the automobile. Oxygen also combines with acetylene to produce a very high temperature. Indeed, the temperature of the oxyacetylene flame (about 3500°C) is one of the highest temperatures that can be produced by chemical means. An oxyacetylene flame cuts through steel (see Fig. 10-6), just as a knife cuts through butter. This property is invaluable in the construction of ship and skyscrapers.

Nor must we forget that oxygen is the breath of life; without it we would perish. The oxygen we inhale passes through the lung membrane and enters the blood stream. The blood carries oxygen to cells in all parts of the body. In the cells, the oxygen combines with some of the products of digestion, forming carbon dioxide and water, and releasing heat. The energy released in this reaction keeps us warm and also provides the vitality that enables us to work and play.

Fig. 10-6. An oxyacetylene flame easily cuts through this steel plate.

Hydrogen

So far we have emphasized the need for oxygen in combustion. A substance that is burned to produce heat is called a *fuel* and the most efficient fuel is hydrogen. Hydrogen, like oxygen, is an element and also a gas at ordinary temperatures. But, unlike oxygen, it is not present in the air. It does, however, form a part of a great many compounds—more compounds than any other element. To obtain the *element* hydrogen, it must be released from one of its compounds. And since water is a compound of hydrogen, it looks as though water can supply all the hydrogen we need.

Hydrogen from Water

The formula for water is H_2O; that is, every molecule of water contains two atoms of hydrogen and one atom of oxygen. If the chemical bond in this compound is broken, both hydrogen and oxygen are released. But how can the bond be broken? The first thing that comes to mind is to heat it, as in the case of potassium chlorate. But it is exceedingly difficult to break this bond by heat, and, even if it were broken, the gases would be mixed and would have to be separated. Fortunately, water molecules can be easily decomposed by electricity and, moreover, in the electrical decomposition of water, the gases hydrogen and oxygen are automatically separated from each other so that they can be collected. Pure water, however, does not conduct electricity but it can be made to do so by the addition of a little sulphuric acid.

The most convenient apparatus for decomposing water and collecting the gases is Hoffmann's apparatus. It consists of two side tubes and a central tube with a large bulb near the top. Pieces of platinum foil and their connecting wires are supported by rubber stoppers which fit into the bottom of the side tubes. The apparatus arrangement is shown in Fig. 10-7.

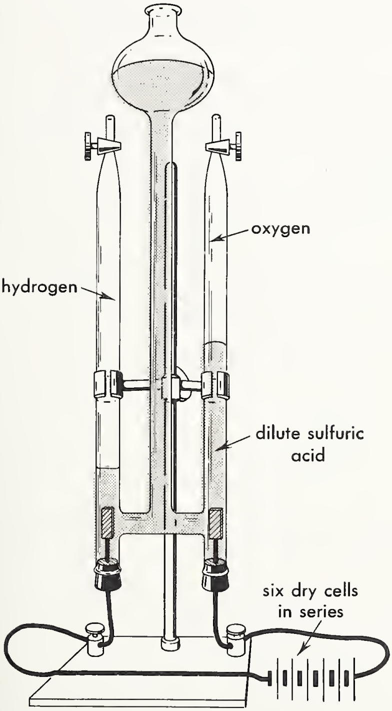

Fig. 10-7. The decomposition of water by an electric current.

Experiment

10-6. To collect hydrogen and oxygen from water

Pour very dilute sulphuric acid into the central tube until the side tubes are filled. Then close the stopcocks of the side tubes. Connect 5 or 6 dry cells in series and then connect the terminals of this battery to the platinum terminals at the base of the side tubes. Gas bubbles form on each of the platinum terminals and a gas collects in each of the side tubes. Notice that the volume of gas collected in one tube is twice the volume in the other. Continue collecting gases until the larger gas volume occupies about three-quarters of the tube. Then disconnect the battery.

The gas with the larger volume is hydrogen. We can test for hydrogen by seeing if it will burn. To do this, hold a burning taper near the outlet tube and turn the stopcock so that the gas escapes slowly. Notice that the gas burns.

Now hold a glowing splinter near the outlet of the other tube and turn the stopcock. The escaping gas relights the glowing splinter and therefore it is oxygen.

Hydrogen as a Fuel Gas

In burning, hydrogen combines chemically with the oxygen of the air around it. A flame is always a sign of a chemical reaction and it also indicates that a great deal of heat is being released in this particular reaction. A word equation for the reaction is: hydrogen + oxygen → water vapor (or hydrogen oxide). In symbols, the equation is

$$H_2 + O_2 \rightarrow H_2O$$

The water vapor formed in the flame then escapes into the air.

Things to Remember

Air consists of 21 per cent oxygen, 78 per cent nitrogen, and 1 per cent of other gases.

An *element* is a substance that cannot be decomposed into simpler substances.

Compounds are formed whenever two or more elements combine with each other chemically.

A *test for oxygen* is that it relights a glowing splinter.

A *catalyst* is a substance that speeds up a chemical reaction.

An *oxide* is a compound of oxygen and another element.

An *atom* is the smallest particle of an element that can take part in a chemical reaction.

In *rapid oxidation* a great deal of heat is evolved suddenly, and there are visible signs of heat.

In *slow oxidation* the rate of reaction is slow and there are no visible signs of heat.

Hydrogen burns but does not support burning; *oxygen* supports burning but does not burn.

Questions

Part A

1. State the approximate composition of air.
2. What is [**a**] an element, [**b**] a compound? Give two examples of each.
3. What is the difference in composition between potassium chloride and potassium chlorate?
4. Describe a simple test for [**a**] oxygen, [**b**] hydrogen.
5. What is a catalyst? Give an example.
6. What is an oxide? Give an example of an oxide of [**a**] a metal, [**b**] a nonmetal.
7. [**a**] What is an atom?
   [**b**] What is the difference between a hydrogen atom and a hydrogen molecule?
8. Write word equations and symbolized equations for the reactions between oxygen and [**a**] sulphur, [**b**] magnesium.
9. What is the difference between rapid and slow oxidation? Give an example of each.
10. Name two steps that can be taken to prevent disintegration of steel by rusting.

Part B

11. Describe an experiment which proves that oxygen is an active ingredient of air.
12. Draw and label a diagram to show how you would prepare and collect oxygen.
13. Concerning your diagram in Question 12, explain [**a**] why water does not fall out of the inverted bottle, and [**b**] why gas bubbles are able to replace this water.

14. Explain why hot carbon will combine with oxygen and why carbon at ordinary temperatures will not.
15. Explain why hydrogen burns and why oxygen does not burn.
16. Describe an experiment in which water is decomposed and hydrogen collected.
17. What is the purpose of the bulb in the center tube of the Hoffmann apparatus described in Question 16?
18. Explain the nature of the chemical reaction in a hydrogen flame. Write a word equation and a symbolized equation for this reaction.

Things to Do

To find the percentage of oxygen and nitrogen in air

Half fill a test tube with water and then pour the water away. Now place a few (very few) iron filings in the test tube and observe that the filings stick to the side of the tube. Invert the test tube and place the open end in a beaker of water. Repeat this procedure with another tube and let the tubes remain overnight in this position.

Notice that, after some hours, the water has risen in the tube. Now fill the beaker with water and raise the test tube until the mouth of the tube is just below the water surface. Close the tube with the thumb, lift the tube out of the water, and invert the tube.

Measure the height of the tube in centimeters and also the height of the water column. Suppose the height of the tube is 14.2 centimeters and the height of the water column is 3.0 centimeters. Then the fraction of oxygen in air is $\frac{3.0}{14.2}$ (or 21 per cent) and the fraction of nitrogen is $\frac{14.2 - 3.0}{14.2} = \frac{11.2}{14.2}$ (or 79 per cent).

Compute the percentage of oxygen and nitrogen from the data of each of the test tubes and find the average percentage values.

11

Fires and their Control

In every chemical reaction heat is either evolved (given out) or absorbed (taken in). If heat is evolved, the temperature rises; if heat is absorbed, the temperature falls. Heat is evolved in more than 90 per cent of all chemical reactions. Reactions of this kind are called ***exothermic*** reactions. The most familiar exothermic reactions are, of course, reactions which involve burning. Let us investigate the phenomenon of burning by examining a candle flame and a Bunsen flame.

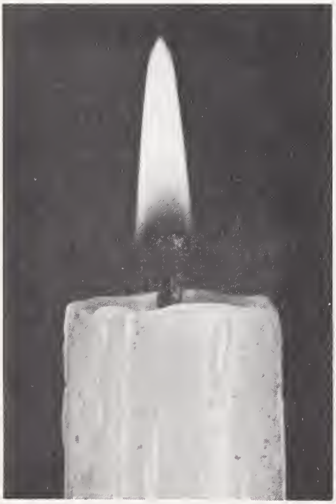

Fig. 11-1. A candle flame.

A Candle Flame

A candle is a piece of paraffin wax through the center of which runs a cotton thread, or wick. When the wick burns it melts some of the paraffin wax. The molten wax rises up the wick, vaporizes, and burns to give a luminous flame. Notice that the candle flame consists of three zones (1) a dark central zone around the wick, (2) a large yellowish luminous zone, and (3) a bluish, almost invisible fringe surrounding the luminous zone, but clearly visible near the base (see Fig. 11-1). How can we account for these different zones?

The dark central zones consists of paraffin vapor. Oxygen of the air is unable to penetrate into this region. That is why the vapor is unburned and appears dark.

Atmospheric oxygen, however, is able to seep into the region of the luminous zone and here a reaction takes place. Paraffin wax is a ***hydrocarbon***, that is, a compound of hydrogen and carbon. There is not enough oxygen to combine with both hydrogen and carbon in paraffin wax and only the hydrogen is oxidized. The carbon is therefore released as free carbon. The word equation for the reaction is: hydrocarbon + oxygen → water vapor + carbon.

Enough heat is released in this reaction to make the minute particles of carbon glow and, in consequence, the carbon zone is luminous. The presence of carbon can be confirmed by holding a piece of porcelain in the flame. Some of the hot carbon is deposited as soot on the cool surface of the porcelain.

The outermost zone is surrounded by air so that any carbon in this zone is completely oxidized to carbon dioxide. The word equation for this reaction is

carbon + oxygen → carbon dioxide

In other words, the outer zone is a region of *complete combustion* whereas the luminous zone is a region of *incomplete combustion*. The presence of carbon dioxide can be proved by the limewater test; carbon dioxide turns limewater milky.

Experiment

11-1. To prove that carbon dioxide is formed in a candle flame

Hold an inverted test tube over a candle flame for a few moments. Pour some limewater into the tube, close the tube with a stopper, and shake it. Notice that the limewater turns milky.

A Gas Burner

A candle is a fair source of light but a poor source of heat. Why is this? A fuel does not yield its potential heat supply unless it is completely burned. A special device is necessary to ensure that a fuel is completely burned; that is, to supply all the oxygen needed for burning. One such device is a gas burner, or Bunsen burner.

The Bunsen burner consists of four parts: (1) a base, (2) a screw valve to control the gas supply, (3) a barrel to mix the fuel gas and air, and (4) openings (air ports) at the base of the barrel to admit air.

When the burner is operating, a mixture of air and fuel gas burns at the top of the barrel. If the air ports are closed, the flame is *luminous* due to white-hot particles of carbon and, like the candle flame, it gives light but little heat. Indeed, the hand can be passed through the flame without discomfort. A luminous flame is of little use in the laboratory where heat, and not light, is usually needed. To change a luminous to a nonluminous flame, the air ports must be opened. Enough oxygen is then supplied to completely burn the carbon particles to carbon dioxide. This additional reaction releases a great deal of heat.

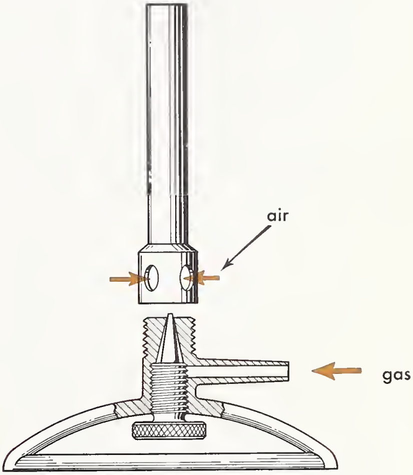

Fig. 11-2. A Bunsen burner.

The hot nonluminous flame is usually referred to as the Bunsen flame. A typical reaction in the Bunsen flame is the burning of natural gas which is mainly methane, CH_4. Notice that methane is a hydrocarbon. The equation for the oxidation of methane, expressed in words, is

methane + oxygen → carbon dioxide
+ water vapor + heat

and, using chemical symbols, the equation is

$$CH_4 + O_2 \rightarrow CO_2 + H_2O + \text{heat}$$

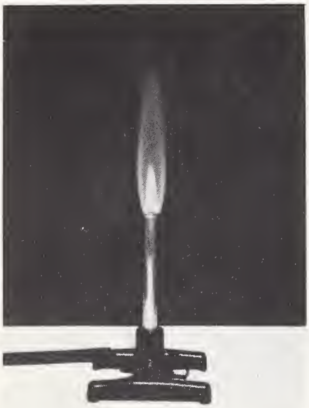

Fig. 11-3. The zones of a Bunsen flame.

The Bunsen flame, shown in Figs. 11-3 and 11-4, consists of four zones: (1) a dark central zone of unburned gas and air; (2) an inner greenish-blue zone where burning first begins; (3) a large dark blue zone of intense burning and (4) an outer light blue fringe of complete combustion.

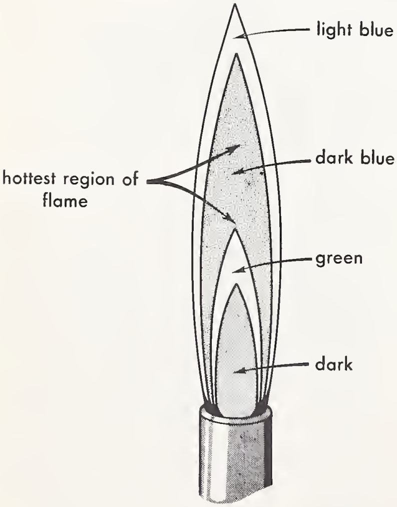

Fig. 11-4. The four zones of a Bunsen flame are clearly shown in this photograph.

The hottest part of the Bunsen flame is just above the top of the greenish zone. A piece of copper wire, which has a melting point of almost 1100°C, will melt in this region, as shown in the following experiment.

Experiment

11-2. To show that the temperature of a Bunsen flame is higher than the melting point of copper

Light a Bunsen burner and adjust the air supply until the flame begins to roar. Push one end of a copper wire, 3 or 4 inches long, into a cork stopper. Holding the wire by the stopper, place the free end of the wire just above the blue inner zone. A globule of molten copper soon collects on the tip of the wire, which proves that the temperature of this region of the flame is, at least, 1100°C.

Household Heaters

Although the Bunsen burner was invented as a convenient source of heat in the laboratory, it has been adapted to use in the home. The gas cooking stove, for example, operates like a Bunsen burner. Here, fuel gas and air are mixed in a pipe, and the mixture is burned at the openings of a ring burner. A ring burner provides a number of small flames arranged in a circle so that the heat is spread out rather than concentrated on one spot.

The flames of a ring burner should not be luminous. Why not? If the flame is luminous, soot is deposited on the cooking utensils; moreover, fuel is being wasted and the flame is not as hot as it should be. The remedy should now be apparent—admit more air. This is done by adjusting the size of the opening that controls the air supply.

Matches

Matches are a relatively recent invention and we accept them today without even thinking of their convenience. Less than two centuries ago fire was commonly produced from sparks obtained by friction between flint and steel. Indeed, this method of starting a fire was handed down from earliest times. Early man used two rocks for this purpose, flint–a form of silica–and pyrites. Pyrites is a mineral rich in iron but it looks like gold and is sometimes called "fool's gold." If the hard flint strikes the softer pyrites, a shower of sparks is produced by the hot particles of pyrites. Ancient man started his fires by directing the sparks onto a heap of dry grass or powdered bark. (The modern cigarette lighter is an adaptation of this ancient device.)

Fire was also made by the method shown in Fig. 11-5. In this contrivance a wooden drill, rotated by the hands, fits into a groove in a flat board. The heat of friction causes wood dust to smolder which, in turn, ignites a tinder of dry grass and bark.

This friction method of starting a fire is still used by backward tribes in Africa and South America. In our own country the hunter and woodsman sometimes light a fire in this way, and a Boy Scout often learns the technique as a part of his training.

The modern match operates on the same principle as these ancient devices but the chemist has simplified the operations. First, various fuels such as wood, phosphorus and sulphur are used. Then there is an oxidizing agent, such as potassium chlorate, to accelerate the rate of burning. Finally, there is friction to generate enough heat to start the burning. The heat of friction raises one of the combustible substances to its ***kindling temperature***. This is an important term and we shall refer to it frequently. ***The kindling temperature of a substance is the temperature to which a substance must be heated before it will burn.***

Matches are of two kinds, (1) the strike-anywhere match and (2) the safety match. Let us first consider the strike-anywhere match.

A wooden stick is first soaked in alum or ammonium phosphate to prevent the match from glowing after it is thrown away. One end of the stick is then soaked in molten paraffin wax to make it burn better. This end is then dipped into a mixture of potassium chlorate and glue. Finally, the tip is dipped into a paste of phosphorus sulphide.

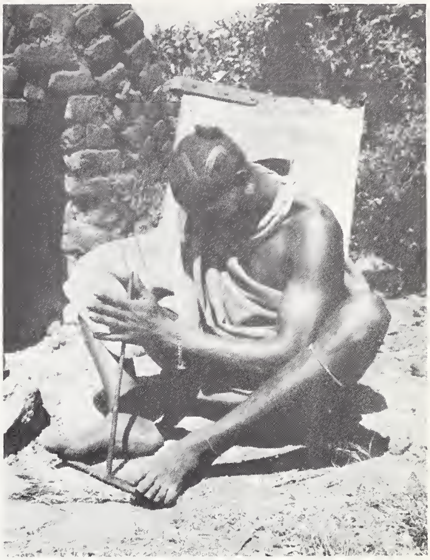

Fig. 11-5. A native African woman making fire by friction.

When the match is struck, the heat of friction ignites the phosphorus sulphide; the potassium chlorate supplies oxygen to increase the rate of burning; the paraffin wax melts and burns, and, finally, the wooden stick is ignited. Have you ever noticed the molten wax that moves ahead of the flame as a match burns?

The safety match is similar to the strike-anywhere match except for one important difference. The phosphorus in the head of the strike-anywhere match is easily ignited by friction. In the safety match it is replaced by antimony sulphide. A safety match is not easily ignited by rubbing it on an ordinary surface. A special surface is therefore prepared from a mixture of red phosphorus, powdered glass, and glue,

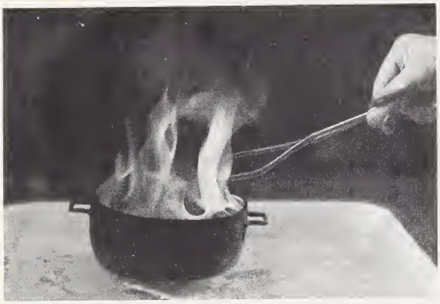

Fig. 11-6. The kerosene flame is extinguished when the bowl is moved about in ice and water.

which is pasted on the side of the box or on the cover of the book. When a match strikes this surface, friction raises some of the phosphorus to its kindling temperature. Phosphorus along the friction track burns and, in doing so, raises the antimony sulphide to its kindling temperature which, in turn, starts the match burning.

Kindling Temperature

It should now be apparent that even a combustible substance cannot burn at temperatures below its kindling point. Hence, any fire can be extinguished if the temperature of the burning fuel is lowered below its kindling temperature.

Every combustible substance has its own particular kindling temperature. Fuel gas, for instance, is inactive at ordinary temperatures and merely escapes into the air without burning. However, a lighted match will ignite the gas because the heat from the burning match raises the temperature of the gas to its ignition point. Gasoline and ether have low kindling temperatures, a property that renders them highly inflammable. They should be handled with great care. Wood and coal, on the other hand, have much higher kindling temperatures; they require strong heating before they will burn. Kerosene has a higher kindling temperature than gasoline and it is quite safe to try the following instructive experiment.

Experiment

11-3. The kindling temperature of kerosene

Pour some kerosene into a beaker and then drop a lighted match into it. The kerosene does not burn, and the match is extinguished. Why?

Now pour the kerosene into a metal bowl and heat it over a Bunsen flame for a few seconds. Again drop a lighted match into the kerosene. This time it burns. Why?

Finally, holding the bowl by a pair of tongs, move it back and forth in a tray containing ice and water. The flames are soon extinguished. Why?

Dust Explosions

If we place a block of wood over a Bunsen flame for a minute or so the wood probably chars but does not burn. Why not? A splint of wood from the block burns at once when held in the flame. Why is this? The splint burns more readily than the block because relatively more of its surface is in contact with air. Particles as fine as dust have relatively very large surface areas exposed to air and they burn violently if heated to their kindling temperature. Suitable dusts for experimental purposes are flour and lycopodium powder. Lycopodium is a club moss, and the powder is formed from spores on the leaves.

Experiment

11-4. The burning of a powder

Place 3 or 4 grams of lycopodium powder in a calcium chloride tube to which a piece of rubber tubing is attached. Direct the tube toward the flame of a ring burner as shown in Fig. 11-7. Blow through the rubber tubing and, as the powder passes through the flame, it burns with a spectacular flash.

It is apparent that combustible particles are a fire hazard, and precautions should be taken against this risk. For example,

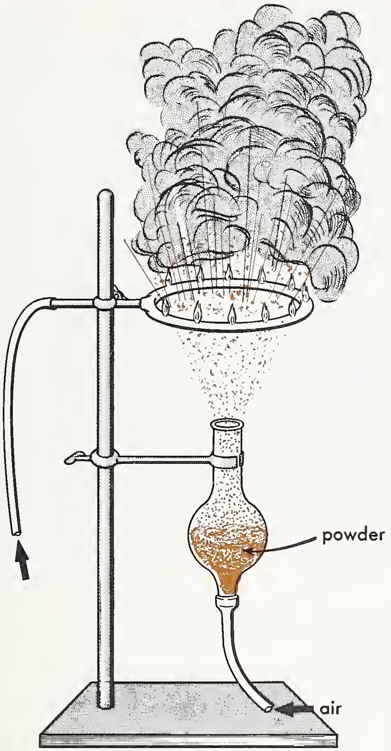

Fig. 11-7. Lycopodium powder burns with a spectacular flash when raised to its kindling temperature.

aluminum and magnesium dusts are formed when these metals are tooled in the construction of airplanes. The heat of friction is enough to raise them to their kindling temperature, and an explosion is likely if they mix with air. The fire hazard is reduced by sucking the metal dusts into a bag as soon as they are formed.

What is Spontaneous Combustion?

Some substances may reach their kindling temperatures without heat being applied. This is clearly another fire hazard. How is this possible? Combustible dusts like coal dust, flour, or even starch slowly oxidize in air. Thus coal particles, which are mostly composed of carbon, slowly react with oxygen of the air to form carbon dioxide. Or,

$$C + O_2 \rightarrow CO_2 + \text{heat}$$

If there is no ventilation (or convection current) to carry away the heat evolved in this reaction, the temperature may rise until the kindling point is reached. Then the coal dust will burst into flame. Coal in ships' bunkers has been known to catch fire in this way. The rolling of the ship sets the coal in motion. As a result, coal dust rises into the air and the process of oxidation begins.

A fire that is started without the help of an external source of heat is called spontaneous combustion. If oily rags are left in a poorly ventilated place, such as a closet or cupboard, spontaneous combustion may occur. The oil, which is a hydrocarbon, slowly oxidizes, and the heat evolved may raise the oil and the rags to their kindling temperatures. The ignition of hay in a barn, or in outdoor stacks, is another example of spontaneous combustion that may cause serious fires. However, since heat is liberated well *inside* a haystack, the reaction cannot be caused by atmospheric oxygen. Instead, it is due to the action of bacteria decomposing the damp hay and, in doing so, enough heat is released to start a fire.

Of all the fires started by spontaneous combustion, probably the most serious ones occur in grain elevators. Flour and grain dust are highly inflammable and strict precautions must be taken against the danger of fire, either from spontaneous combustion or from sparks caused by friction in the machinery.

The Control of Fire

Fire under control is a boon to mankind, but fire out of hand is one of his greatest enemies. Through the ages there have been many disastrous fires. For example, in the year 64 A.D. during the reign of Nero, more than half the city of Rome was ruined by

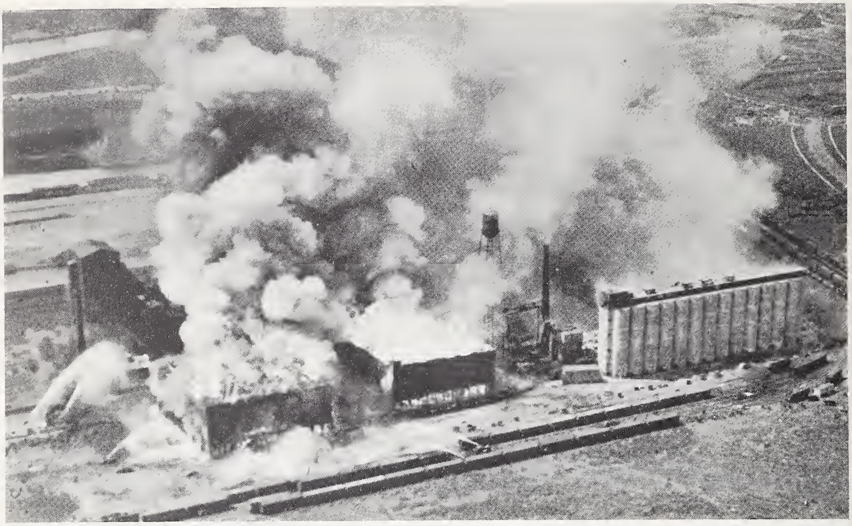

Fig. 11-8. A fire following a dust explosion in a grain elevator.

a fire that raged for six days. In the seventeenth century the Great Fire of London burned for 14 days leaving 200,000 people homeless; and less than 100 years ago, the city of Chicago was completely destroyed by fire in a single night.

The concrete structures of today make it unlikely that whole cities will again be gutted. Nevertheless, fire losses in Canada are staggering; they amount to millions of dollars a year. Most of this destruction is attributed to carelessness and so could have been prevented. By far the greatest fire hazards are cigarette stubs or matches thrown away while still burning or smoldering. We can think of many other ways in which fires may be started; campers failing to extinguish their fires may start forest fires; a house may have a defective chimney, or its electric wiring may be faulty; electric heating appliances may be left with the current on. Combustible substances are all around us and a destructive fire may be started if only a small fraction of this substance is raised to its kindling temperature.

Fire laws are passed to protect life in industrial plants and public places. But these do little to reduce the hazards due to negligence in the home or in the countryside.

Protection against fire has long been recognized as a community problem. Fire departments in every town carry a great deal of equipment, including powerful pumps that can throw water to a great height. Without an ample supply of water a fire department is helpless. In the San Francisco earthquake of 1906, water mains were broken and, as a result, the fire which followed the earthquake got out of control, causing widespread damage.

Skyscrapers present a special problem in fire protection; even the most powerful pumps cannot reach their upper floors. Tanks of water are therefore stored under the roof so that, in case of fire, the upper floors may be flooded.

Have you ever noticed the water pipes, with their numerous outlets, supported near the ceilings of department stores? They are probably part of a sprinkler system, an automatic fire-control device. The jets are sealed with an alloy that has a low melting point, below the temperature of

Fig. 11-9. Fire fighting. Powerful pumps on the fire truck force the water to a great height.

boiling water. Hence the alloy melts before a fire really gets underway; water then issues through the jets and the fire is quenched.

Water is commonly used for fighting fires. Water lowers the temperature of a burning substance below its kindling temperature; moreover, it wets the combustible material and makes it more difficult to burn. But the lavish use of water causes much damage in a home and there are better ways of dealing with small fires than using water.

To Exclude Air from a Burning Substance

If air is excluded from a substance, it cannot burn, no matter how high the temperature. You may have noticed that blankets are often supplied as a safety precaution in laboratories. An inflammable liquid spilled on one's clothing may catch fire. The simplest way to put out the flames is to wrap a blanket, or even a coat, tightly over them.

This method of putting out a fire is shown in Experiment 11-5. Here a gasoline fire is extinguished if the air supply is shut off by even a filter paper. While paper applied in this way is a striking example of an important principle, it must not be used for this purpose on a large scale. Why not? Be sure to have a fire extinguisher at hand before attempting the following demonstrations on fire.

Experiment

11-5. To extinguish a gasoline fire by excluding air

Make a mixture of about equal quantities of gasoline and kerosene. Pour a little of the mixture into a 1-liter beaker and ignite it by dropping a burning match into it. Cover the beaker with a filter paper and observe that the flame is immediately extinguished.

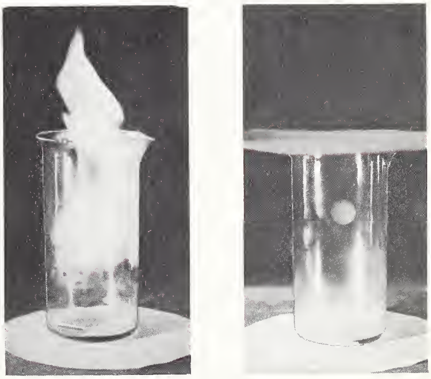

Fig. 11-10. Even a filter paper placed over the beaker excludes the air and puts out the flame.

Fire Extinguishers

Fire extinguishers are safety devices required in factories, public buildings, schools, airplanes, and railroad trains. They ought also to be conveniently placed in every house. By far the most common extinguisher is one that generates carbon dioxide. Fires, however, need special treatment depending on the nature of the fuel, and it is not surprising that there are several kinds of carbon dioxide extinguishers. The one that serves most purposes is the soda-acid extinguisher.

What is an Acid?

An acid is an essential ingredient in a soda-acid extinguisher. The first acid used by man was probably acetic acid which occurs in vinegar. Vinegar is formed when wine oxidizes and turns sour. It was known to the Greeks and Romans; indeed it was an ingredient of one of their favorite drinks.

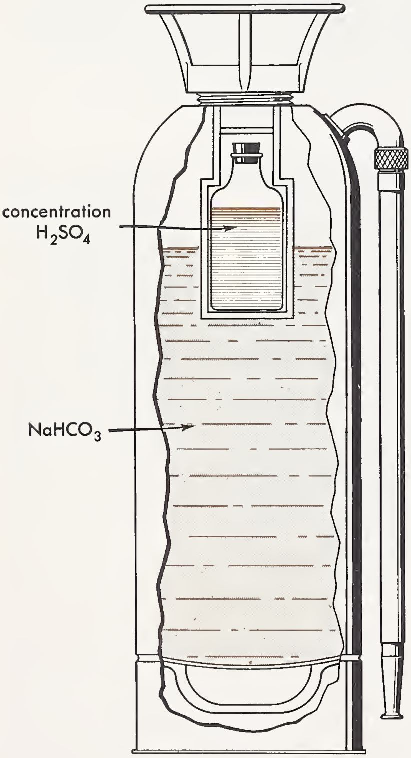

Fig. 11-11. A soda-acid extinguisher.

In industry the most important acids are sulphuric, hydrochloric, and nitric acids. These are manufactured from minerals and, for this reason, are called mineral acids. They may be ***concentrated***, in which case a relatively small proportion of water is present with the acid, or ***dilute***, in which case a large proportion of water is mixed with the acid.

If an acid is poured on baking soda, a brisk reaction takes place and carbon dioxide is evolved. Carbon dioxide is much denser than air. This property is used in extinguishing a fire because carbon dioxide will displace air and smother a flame as shown in the following experiment.

Experiment

11-6. Carbon dioxide extinguishes a candle flame

Take a candle, 1 or 2 inches long, light it, and place it on the bottom of a beaker. (A 600-cc. beaker is suitable.) Sprinkle some baking soda on the bottom of the beaker and then pour in some vinegar. A brisk reaction takes place. The heavier carbon dioxide displaces the air, smothering the flame so that it is extinguished.

The Soda-Acid Extinguisher

The essential ingredients in this extinguisher are baking soda ($NaHCO_3$) and an acid, usually sulphuric acid. (This reaction can be carried out in a test tube and the presence of carbon dioxide confirmed by leading it into limewater. Carbon dioxide turns limewater milky.)

The extinguisher itself is a copper vessel containing about 2 gallons of baking soda solution. A metal basket, near the top of the container, supports a bottle of concentrated sulphuric acid. The bottle has a loosely fitting stopper. When the extinguisher is inverted the liquids mix, a reaction takes place, and carbon dioxide collects above the solution. The pressure of the carbon dioxide is considerable; it ejects the solution through a flexible hose

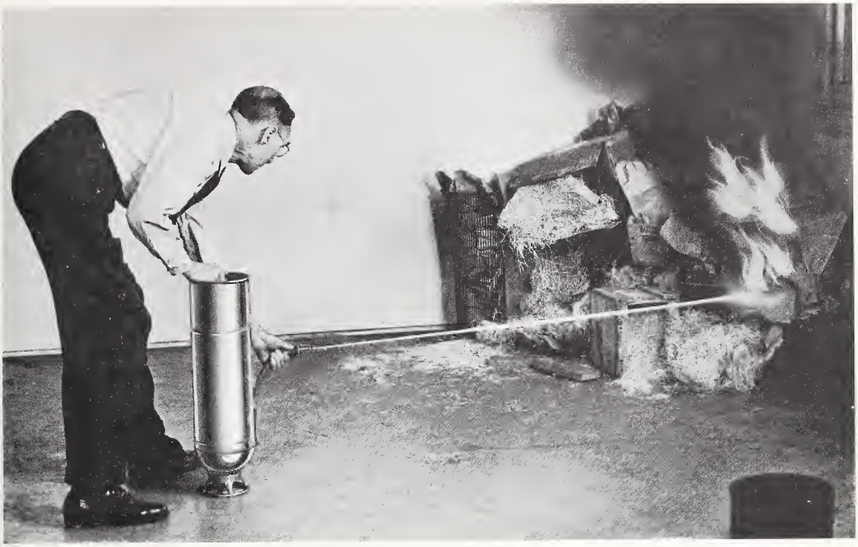

Fig. 11-12. When a soda-acid extinguisher is inverted, the solution is forced out under considerable pressure.

a distance of 30 or 40 feet and onto the fire. The principle of the soda-acid extinguisher can be shown in the following experiment.

Experiment

11-7. A home-made extinguisher

Pour a baking-soda solution into a milk bottle and lower a test tube containing vinegar into the bottle. Securely close the bottle with a rubber stopper into which is fitted a right-angle glass bend. The arrangement is shown in Fig. 11-13.

Place some excelsior in a baking pan and ignite it. Invert the bottle and direct the stream toward the fire. The blaze is readily extinguished.

A Foamite Extinguisher

The main function of carbon dioxide in the soda-acid extinguisher is to supply enough pressure to force the solution out of the tank. In other words, the real extinguishing agent is water. Water, however, would be useless against a gasoline fire; it would merely sink below the burning gasoline. Why? Gasoline fires can be held in check by a foam of carbon dioxide bubbles which float on gasoline and smother the the fire. Such a foam is supplied by a foamite extinguisher.

Foamite and soda-acid extinguishers are similar in appearance. The foamite ingredients, however, are solutions of baking soda and alum, in separate containers. When the extinguisher is inverted the ingredients mix and react to form carbon dioxide. In this reaction, carbon dioxide is released as millions of tiny bubbles which adhere to form a foam. A little glue added to the alum solution makes the bubbles stronger so that the foam will remain intact for an hour or so, and even stick to a vertical surface. Foamite extinguishers are commonly used in plants where inflammable liquids like gasoline, oil, and tar are used or produced.

Experiment

11-8. To make foamite

Make up an alum solution (80 grams per

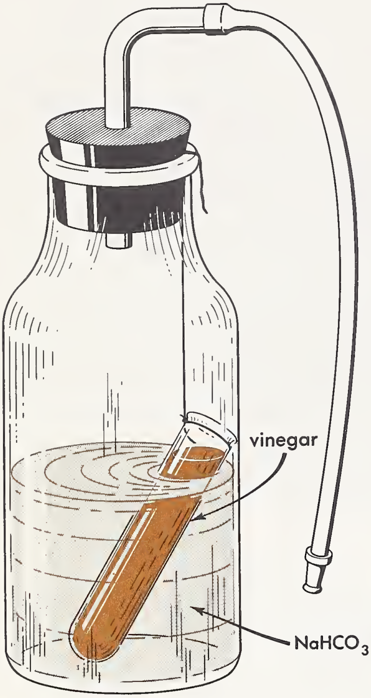

Fig. 11-13. A simple soda-acid extinguisher can be made out of a milk bottle.

liter) and add enough liquid glue to make it sticky. Also make up a baking-soda solution (120 grams per liter).

Pour about 100 cubic centimeters of the alum solution into a tall glass cylinder (about 1-liter volume) and then add 100 cc. of baking soda solution. A foam of carbon dioxide bubbles rises to the top of the cylinder as shown in Fig. 11-14.

A Dry Carbon Dioxide Extinguisher

The best all-purpose extinguisher contains only liquid carbon dioxide. It can cope with rubbish fires, gasoline fires, and also fires of electrical origin. Neither the soda-acid nor foamite extinguishers should be used to fight fires that have started in a switchboard or in electrical household appliances. Solutions in these extinguishers conduct electricity and a dangerously large current might easily be carried to the operator.

In the dry carbon dioxide extinguisher the gas is compressed to a liquid under a high pressure. When the outlet valve is opened, liquid carbon dioxide changes to gas. As the gas expands it cools to such an extent that some of it is changed to the solid form "dry ice." This is very effective in lowering the temperature of the combustible substance below its kindling temperature and in cutting off the supply of oxygen.

A Carbon Tetrachloride Extinguisher

Carbon tetrachloride is the main constituent of various extinguishers such as Pyrene or Fyr-Fyter. Carbon tetrachloride forms a heavy noncombustible vapor which, like carbon dioxide, excludes air from a flame and extinguishes it. This vapor is more efficient than carbon dioxide

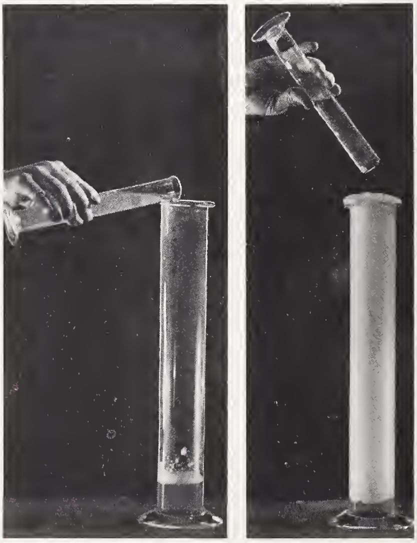

Fig. 11-14. Foamite. On the left, sodium bicarbonate solution is being poured into alum solution, and a foam is beginning to form. On the right, foamite completely fills the cylinder.

since it is three times heavier. It is a nonconductor of electricity and can be safely used in fighting fires of electrical origin. Moreover, it is a "dry" chemical and causes no water damage; that is, it does not injure woodwork, draperies, or upholstery and, for this reason, it is the popular extinguisher in houses. Since it also extinguishes oil and gasoline fires, it is often carried in airplanes, railway coaches, and automobiles. The common extinguisher of this type usually carries about a quart of liquid which is ejected by pump action.

At high temperatures carbon tetrachloride reacts with oxygen of the air to form a poisonous gas called phosgene. The small amount of phosgene formed in an ordinary fire is relatively harmless. Nevertheless, users of this type of extinguisher should be aware of the risk, particularly when it is used in a poorly ventilated place.

Experiment

11-9. Carbon tetrachloride as a fire extinguisher

Ignite a large filter paper and drop it into a tall 1-liter beaker. Pour enough carbon tetrachloride over the paper to extinguish the flame. Notice the heavy vapor of the tetrachloride, made visible by smoke particles.

Into another tall beaker pour about 10 cubic centimeters of gasoline and ignite it. Now pour the carbon tetrachloride vapor over the gasoline flame which is extinguished at once.

Flameproofing

Fire laws usually require that drop curtains in theaters and drapes in hotels and restaurants be treated with a flameproofing chemical such as ammonium phosphate. The drapes or curtains are either dipped into a solution of the compound or sprayed with it. Wood used to construct airline hangars is also usually rendered flameproof by injecting the solution into the wood under pressure.

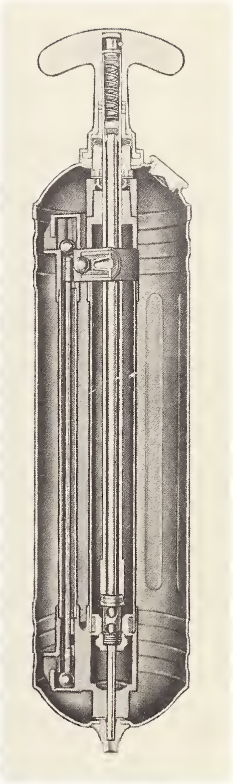

Fig. 11-15. A pyrene extinguisher contains about one quart of carbon tetrachloride, which is squirted onto the burning material by pumping the handle.

Things to Remember

An *exothermic reaction* is one in which heat is evolved.

A *hydrocarbon* is a compound of hydrogen and carbon.

The *kindling temperature* of a substance is the temperature to which the substance must be heated before it will burn.

Spontaneous combustion is a fire started without the help of an external source of heat.

Fires can be controlled either by cooling the burning substance below its kindling temperature, or by excluding air from it.

The *common types of fire extinguishers* are [**1**] soda-acid, [**2**] foamite, [**3**] dry carbon dioxide, [**4**] carbon tetrachloride.

Questions

Part A

1. What is an exothermic reaction? Give an example.
2. What is meant by the terms *complete combustion* and *incomplete combustion*?
3. [**a**] Define the term *kindling temperature*.
   [**b**] Write down three liquids in order of their kindling temperatures, the one with the lowest kindling temperature first.
4. Give an example of spontaneous combustion.
5. Either one of two procedures will put out a fire. What are they?
6. What are the three advantages of a dry carbon dioxide extinguisher over a soda-acid extinguisher?

Part B

7. [**a**] Draw and label the parts of a candle flame.
   [**b**] Discuss the chemical reactions that take place in the flame.
8. What is a safety match? How does it operate?
9. Describe an experiment to prove that the flames of a burning liquid are extinguished if it is cooled below its kindling temperature.
10. Explain carefully why flour dust is a fire hazard.
11. Describe a soda-acid extinguisher. How does it operate? Draw a diagram.
12. What is foamite? What is its particular advantage as a fire extinguisher?

Things to Do

Visit to a fire department

Obtain permission to visit your local fire department, and ask the fire chief to explain the various devices for fighting fires. Are some firemen on duty at the station at all hours of the day and night? Are all firemen on call in case of fire? What is the usual procedure when the department is warned of a fire?

12

Coal, a Fossil Fuel

Through the ages man has invented more and more machines to do his work. Today, there are machines everywhere; indeed a marked characteristic of modern civilization is its high degree of mechanization. Machines, however, are driven by engines, and engines need a fuel to supply the necessary heat energy. The fuel that powered the industrial revolution in the eighteenth and nineteenth centuries was coal. At the turn of the present century coal was still the king of fuels–90 per cent of the heat energy used in Canada and the United States was supplied by coal. What is coal? How was it formed?

The Origin of Coal

Coal is a fossil fuel formed during a geological era (the Carboniferous Period), about 300 million years ago. At that time the earth's surface was warmer than it is now and the atmosphere contained a higher percentage of carbon dioxide which, you may recall, is the essential food of all vegetation. There were vast stretches of low-lying swampy land in which rank vegetation such as rushes and giant ferns grew and flourished. The surface of the earth was still in the process of settling in these early times. As the land settled, the sea flooded the swamps burying the accumulated plant debris in mud or sand. In the course of time, the sinking process was followed by uplift and again vegetation thrived in the lowlands. Thus, these areas were alternately covered by sea and land, and the vegetable matter was forced to greater and greater depths. Under this high pressure, mud and sand were changed to shale and sandstone and vegetable matter was slowly changed to coal.

Coal is found in beds (or seams), separated from each other by layers of rock. Coal beds vary in thickness up to as much as 50 feet. Every coal seam represents a long period of plant growth followed by a settling of the land. Usually there are several seams one above another. In some regions there are as many as 30 of them, indicating that the coal field was formed over an incredibly long period of time.

Kinds of Coal

There are four broad classes of coal, depending on the extent of change in the original vegetation. These are peat, lignite, bituminous, and anthracite. The amount of carbon shows a steady increase through these stages: from 50 per cent in wood to, roughly, 60 per cent in peat, 70 per cent in lignite, 85 per cent in bituminous, and 95 per cent in anthracite.

Peat is a spongy substance of low heat (or carbon) content. It represents the first stage in the conversion of vegetation to coal. It is found in bogs in many parts of the world, particularly in Ireland where it is dried in the sun and used as a fuel.

Lignite is a dark brown substance between peat and true coal. It is not a good fuel because of its low carbon content. In Europe it is used for making synthetic gasoline and is very satisfactory for this purpose. Enormous deposits of lignite, largely untapped, underly parts of Wyoming, Montana, and North Dakota, just south of the Canadian border.

Bituminous is the most important variety of coal. It is soft and widely used as a fuel. Its importance lies in the fact that when distilled, it gives off gases and tars that are used in many chemical industries.

Anthracite, or hard coal, is almost pure carbon. For this reason it is used only as a fuel; that is, its uses are limited to heating and cooking. The largest anthracite beds in North America are in the United States.

How is Coal Formed?

The constituents of coal are carbon, oxygen, hydrogen, nitrogen, a small amount of sulphur, and traces of other elements. All these are derived from vegetable and woody material that is largely composed of cellulose, $C_6H_{10}O_5$.

If vegetable material decomposes in air, most of the carbon oxidizes to carbon dioxide, and no coal is formed. If, however, air is excluded by a covering of water, or debris, or earth, only partial decomposition takes place, and water and carbon dioxide appear to be "squeezed out" when H_2O and CO_2 are formed. It is apparent that if H_2O and CO_2 are gradually removed from $C_6H_{10}O_5$, the remaining substance becomes poorer in oxygen and richer in carbon. The following table, which shows the analysis of the varieties of coal, proves this to be the case.

	Percentages of			
	Carbon	Oxygen	Hydrogen	Nitrogen
Wood	50	43	6	1
Peat	57	35	7	1
Lignite	70	23	6	2
Bituminous	85	7	6	2
Anthracite	94	1	4	1

These figures show the importance of carbon in all types of coal. Carbon is the backbone of many industrial processes. In one form or another, carbon compounds make up about 95 per cent of the products of industry.

Where is Coal Found?

The striking fact about coal is that all that has been mined to date is almost insignificant compared with the vast reserves still underground; there is enough coal to meet the world's needs for centuries to come. However, coal is unevenly distributed throughout the earth. Most of it is in the temperate zones; some is in the Arctic and Antarctic, and relatively little in the tropics. The vast European coal field stretching from Great Britain to Belgium, to France, to the Ruhr in Germany, and on to the Ukraine in Russia has been worked for more than a century. This is one of the regions where the reserves are noticeably dwindling and where in some parts—for example England—they are approaching exhaustion.

About one-third of the world's coal is in Asia, mostly in China. In Asia, however, industrialization has lagged and these vast deposits still remain to be exploited.

Both Canada and the United States are amply supplied with coal; between them they hold more than one-half of the known coal reserves in the world. In Canada coal is mined in all areas except the province of Quebec, and the Yukon and Northwest Territories. But the coal output in Alberta and Nova Scotia exceeds by far the output of the other provinces. The map on page 115 shows both the coal fields and the gas fields in Canada.

Coal Mining

Underground coal mining is a dangerous

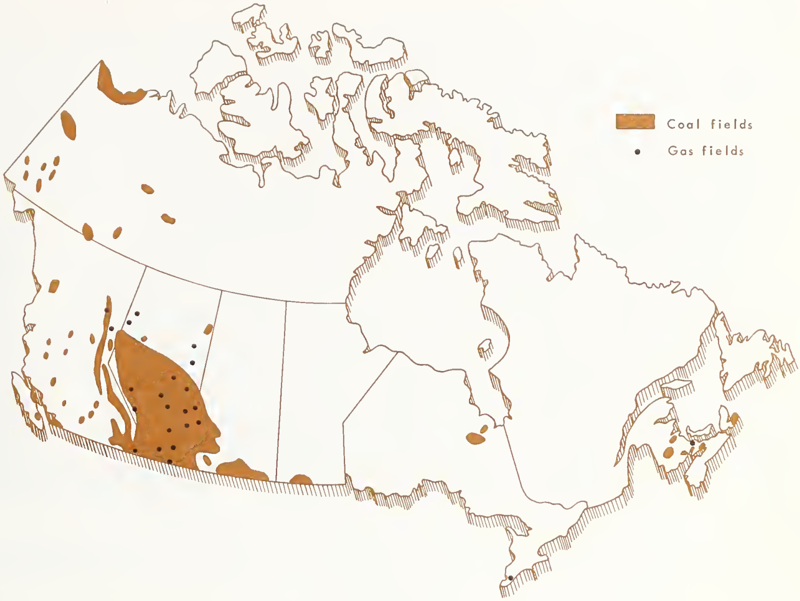

Fig. 12-1. Coal fields in Canada.

occupation in spite of precautions to reduce the risks. There is the ever-present danger of flooding. Water trapped within rock strata is often released during mining operations, and enormous quantities of it must constantly be pumped out of the mine. James Watt's steam engine was originally designed for this purpose as early as 1776.

Another danger is the risk of explosion of mine gases such as methane (CH_4). Methane is one of the substances formed when vegetation decomposes under water. That is why it is associated with marshes and is often called marsh gas. Methane found in coal mines was probably formed in the same way and, since the gas could not escape, it was absorbed by the coal. During mining operations the gas is released. If enough of it accumulates to reach explosive proportions, a spark from a cutting machine may ignite it. Owing to the limited air supply combustion is incomplete so that carbon monoxide (CO) as well as carbon dioxide is formed. A word equation for this reaction is

methane + oxygen → water vapor
+ carbon dioxide + carbon monoxide

A symbolized equation for the same reaction is

$$CH_4 + O_2 \rightarrow H_2O + CO_2 + CO$$

Carbon monoxide is exceedingly poisonous and often takes a high toll of life after a mine explosion. A miner refers to the combustible gas methane as *firedamp*; the dreaded carbon monoxide is called *afterdamp*. ("Damp" is an old English word meaning gas.)

Coal dust is formed by cutting machines and by loading coal on cars. This is another hazard, since it may be ignited by spontaneous combustion or by the explo-

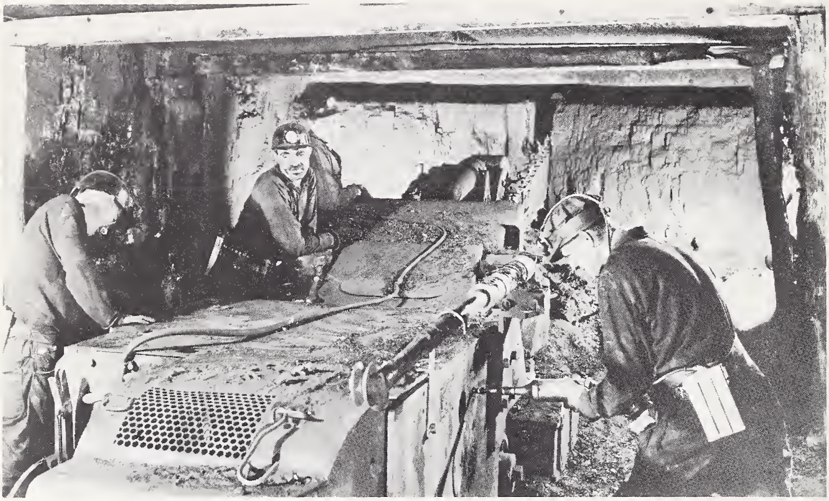

Fig. 12-2. A coal-cutting machine. Horizontal and vertical gashes are made in a coal seam before it is blasted.

sion of a blasting charge. Coal dust explosions can be localized by scattering rock dust, such as powdered limestone, on the walls and floor of a mine. During the explosion, rock dust is thrown into the air and mixes with coal dust. Being incombustible, the rock dust prevents the explosion from spreading through the mine.

What is Coal Used for?

Until recently the largest consumers of coal were steam locomotives. But steam locomotives have now been largely replaced by oil burning diesels on the railroads. In many other fields as well, oil has supplanted coal as the main source of heat energy. Nevertheless, the annual coal output in Canada is more than 20 million tons. Only about one-third of the total coal production is used as a fuel, mainly for generating electric power. In this process, the heat of burning coal converts water to steam, rotates the wheels of a turbine which, in turn, operates a generator to produce electricity.

Almost another third of the total production is consumed in the steel industry; about one ton of coal is needed for every ton of steel manufactured. Here coal is changed to coke, which is used in the blast furnaces to reduce iron ore to molten iron. Coal is also needed to supply the raw materials in many chemical industries. These materials are obtained by distilling coal.

Distillation of Coal

If coal is heated in a closed vessel, it cannot burn because it lacks oxygen. Instead, the coal is baked and breaks up to form (1) a solid residue called *coke*, (2) a mixture of liquids called *tar*, and (3) a gaseous mixture called *coal gas*. This process of baking and decomposition is known as *destructive distillation*, which may be defined as follows: ***Destructive distillation is the decomposition of a complex substance by heat in a closed vessel and the condensation of some of the vapors.*** This is an exceedingly important chemical process and it can easily be performed in the laboratory.

Experiment

12-1. The destructive distillation of coal

Pack powdered soft coal into a pyrex test tube. Clamp the tube to a stand, and connect it to a condensing bottle which has a glass jet outlet. The arrangement is shown in Fig. 12-3. Heat the tube strongly. Heavy vapors arise, some of which condense in the bottle to form a tar. Coal gas escapes at the outlet and can be ignited. The black residue in the test tube is coke.

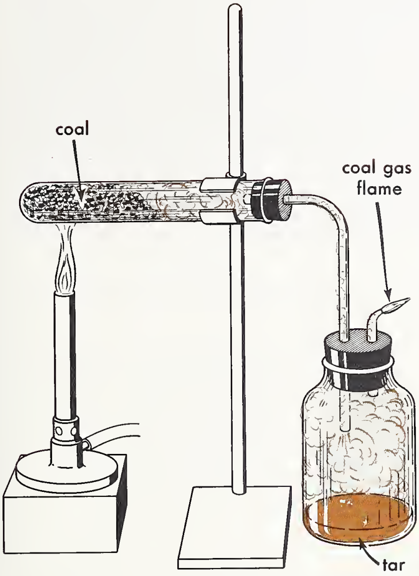

Fig. 12-3. The distillation of coal in a test tube.

By-product Coke Ovens

The distillation of coal is now a vast enterprise and literally dozens of industries depend upon the chemicals extracted from the tar. In industry, distillation is carried out in so-called by-product coke ovens. These ovens are rectangular brick structures about 40 feet long, 12 feet high, and only 18 inches wide. Usually about 50 to 80 ovens are built side by side with narrow heating chambers between them. A battery of coke ovens is shown in Fig. 12-4.

The ovens are filled with bituminous coal, about 20 tons of coal per oven. Fuel gas is burned in the chambers and heat is transmitted to the coal through the brick walls. The temperature of the coal rises to about 2500°F and it is baked for about 18 hours. During the heating, coal softens to a thick tar, and bubbles of gas and vapors escape through outlets at the top of the oven. The volatile products are piped to a chemical plant where they are treated to give coal gas, light oil, and tar.

When the baking is finished, doors at the ends of the oven are opened and a ram pushes the hot coke into a nearby car, as shown in Fig. 12-5. The coke is then taken to a quenching tower and drenched with water, otherwise it would burn away. In the distillation process about 70 per cent of the weight of the coal is obtained as coke, 17 per cent as gas, and about 7 per cent as tar.

Coke

Coke is a tough, porous form of carbon. In the blast furnace it reacts with iron ore (Fe_2O_3) to form molten metallic iron. An equation for this reaction is

iron oxide + coke → iron + carbon dioxide

Or, in symbols,

$$Fe_2O_3 + 3C \rightarrow 4Fe + CO_2$$

The coke must bear heavy loads of iron ore and limestone without being crushed. If it were crushed, it would no longer be porous; gases could not pass through, and the smelting operation would be impossible. Not all coals are coking coals; that is, not all coals form a hard porous lump when heated. Some form a soft coke, and some form no coke at all. The steel industry is seriously concerned at the limited reserves of high-grade coking coal.

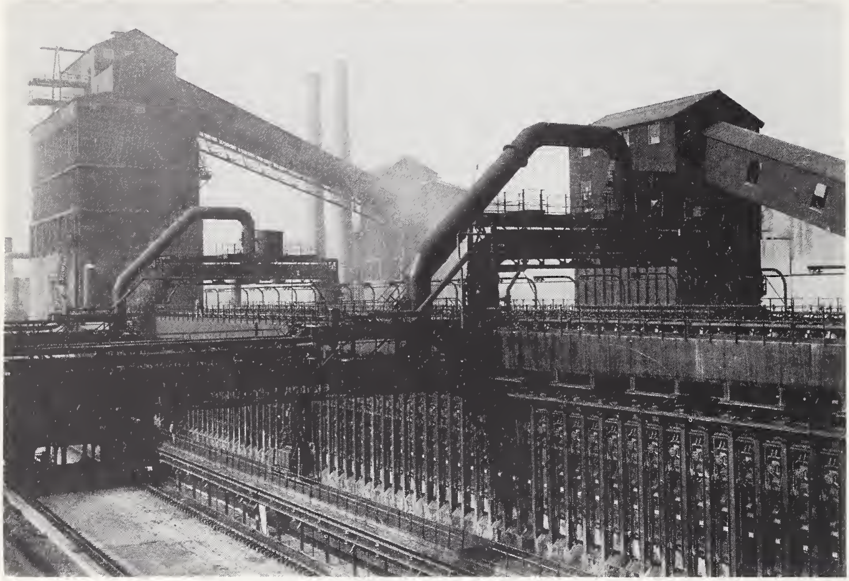

Fig. 12-4. By-product coke ovens. Notice the large number of tall, narrow, rectangular ovens in which coal is distilled.

Coal Gas

Coal gas is the oldest of the fuel gases. It was first obtained from the distillation of coal about the end of the eighteenth century, and soon afterward it was used for street lighting. In 1807 oil then used in the lamps and lanterns of Pall Mall, the well-known street in London, was replaced by coal gas. Londoners, however, were afraid of it, and even well-known scientists wrote the newspapers warning people against the danger of this explosive gas in public places. In the United States it was first used in 1817 for street lighting in Baltimore; later it was used in Boston and New York. It was some years before the newfangled gas won public confidence and it was not until 1850, or thereabouts, that people would have it installed in their houses. Even in houses it was first used only as an illuminant but gradually its value as a fuel came to be realized.

Coal gas is a mixture of substances. Its chief ingredients are hydrogen (about 50 per cent by volume), methane (about 35 per cent) and carbon monoxide (about 6 per cent). All these substances burn with a hot flame. The three reactions in the coal gas flame are

1. hydrogen + oxygen → water vapor + heat
   or,
   $H_2 + O_2 \rightarrow H_2O + \text{heat}$
2. methane + oxygen → carbon dioxide + water vapor + heat
   or,
   $CH_4 + O_2 \rightarrow CO_2 + H_2O + \text{heat}$
3. carbon monoxide + oxygen → carbon dioxide + heat
   or,
   $CO + O_2 \rightarrow CO_2 + \text{heat}$

Coal gas is one of the richest gases; its heat value is about 900 Btu.* per cubic foot. That is to say, if one cubic foot of coal gas is completely burned, 900 Btu.'s of heat are released; enough to raise 900 pounds of water 1°F.

As a fuel it is used in a number of industries. For example, it is used in the gas chambers of the coke ovens. This is a convenient arrangement, since the same gas that is a decomposition product in the ovens is also used to bring about further decomposition of the coal.

Coal Tar and Light Oil

Most of the tar condenses in a receiver near the coke ovens. The coal gas, however, does not condense but moves along the line for treatment and purification. The crude coal gas contains valuable ingredients which must be removed before the gas is burned. To do this the gas is passed up a tower, down which a petroleum oil falls. The petroleum oil dissolves and removes the useful ingredients from the coal gas, which is then stored in enormous gas holders.

The solution of ingredients and oil is now distilled. The low boiling ingredients pass over as a vapor and are condensed to a liquid called *light oil*. By further distillation of light oil, three valuable ingredients—benzene, toluene, and xylene—are separated. From the heavy oil, such products as phenol, naphthalene, and anthracene are recovered.

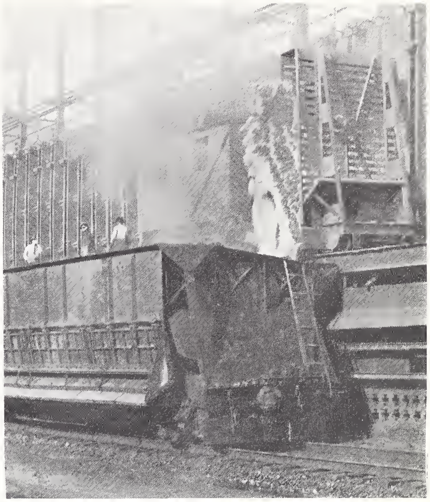

Fig. 12-5. About 10 tons of red-hot coke are being pushed out of an oven by a ram. The coke will be used in blast furnaces.

Even the residual tar is valuable. It is used in road building; that is to say, roads are primed with tar and then covered with sand, gravel, or stone. Creosote, also obtained from tar, protects timber against fungi and termites; railroad ties, telephone poles, and other structural timbers are treated with it. Finally, pitch is obtained from tar. Pitch offers protection against water and, for this reason, it is used on the decks of ships and sometimes in the foundations of buildings and on roofs of houses.

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*See page 172 for the meaning of Btu., which stands for British thermal unit.

Things to Remember

Coal is formed by the slow decomposition of plant material compressed by overlying layers of rock.

Vegetation first changes to ***peat***, then to ***lignite***, then to ***bituminous***, and finally to ***anthracite***.

Destructive distillation is the decomposition of a complex substance by heat and the condensation of some of the vapors.

Coke, tar, and coal gas are formed in the ***distillation of coal.***

Coal gas is a mixture of hydrogen, methane, and carbon monoxide.

Questions

Part A

1. What is the approximate percentage of carbon in [**a**] wood, [**b**] peat, [**c**] lignite, [**d**] bituminous, [**e**] anthracite?
2. What are the chief uses of [**a**] anthracite, [**b**] lignite, [**c**] bituminous?
3. [**a**] What is destructive distillation?
   [**b**] Name the three products (solid, liquid, and gas) obtained from the distillation of coal.
4. What is [**a**] firedamp, [**b**] afterdamp?
5. Write briefly on the location of the main coal deposits in Canada.

Part B

6. Discuss the conditions during the Carboniferous Period that led to the formation of coal.
7. If vegetation is covered by thick sediments, it decomposes; the residue becomes richer in carbon but poorer in oxygen. Explain why.
8. What steps are taken to combat the three imminent dangers in coal mining?
9. [**a**] Why must coal be heated in absence of air to obtain by-products?
   [**b**] What would happen if coal were heated in air?
10. [**a**] What is coke?
    [**b**] What are its important properties and how are they applied in the smelting of iron ore?
11. What are by-product coke ovens? Discuss their operation.
12. Write word and symbolized equations for the burning of the three main ingredients of coal gas.

Things to Do

Destructive distillation of wood

Wood, like coal, can be destructively distilled. To do this, use the apparatus similar to that in Experiment 12-1. Fill the first test tube with sawdust or wooden splinters, and heat the wood strongly. Notice that the wood changes to charcoal and a gas (wood gas) escapes at the outlet and can be ignited. Wood tar and a watery liquid collect in the bottle; they are distillation products. Test the liquid with blue litmus paper and show it is acidic. The acid is acetic acid, an important substance in many chemical industries. At one time the distillation of wood was the industrial method of making acetic acid.

13

Oil and Natural Gas

Oil has been known for centuries. In some places it seeped through the earth and formed pools of oil or sticky puddles of tar; in others, oil vapor and natural gas leaked through the rocks and caught fire, probably when struck by lightning. In Russia, near the Caspian Sea, such fires, fed by an underground pool of oil, burned for many centuries. In Iraq, once called Mesopotamia, asphalt and tar were used as mortar to hold brick and stones together as early as 4000 B.C. It was also found that boats calked with tar were made waterproof and more sea-worthy, so that man dared to take comparatively long journeys by sea. The practice of calking ships was developed particularly by the Phoenicians, who settled along the north Syrian coast about 2000 B.C. They became the merchants of the Mediterranean Sea, bartering goods with the Egyptians and the Greeks.

Oil has long supplied light to mankind. At first, reeds were dipped into oil and used as torches. Later, oil was burned in lamps. The early American settlers used whale oil and also oil that seeped from the ground for their lamps, but the supply was not nearly enough for their everyday needs. When the seepage oil was used up, someone thought of digging into the earth to find the pools that had supplied these surface deposits.

This idea led to one of the world's largest industries. Many years elapsed, however, before men succeeded in bringing oil to the surface, for there were a number of engineering problems to be solved. In 1857 James M. Williams was producing and refining oil in Lambton County in Western Ontario. A Toronto newspaper, *The Globe,* reported in 1858 that Williams had drilled two wells, 100 and 150 feet deep. This marked the beginning of North America's petroleum history.

Williams was interested in oil as a source of kerosene for lamps to replace the tallow candles and whale oil which were then in use. When the internal combustion engine and the automobile were invented, the demand for oil increased enormously. Today, both in Canada and the United States, oil has supplanted coal as the chief source of heat energy. It furnishes power to planes, automobiles, ships and locomotives; it is used to heat factories, hotels and houses. It lubricates all kinds of machinery and, like coal, it is the basis of vast chemical industries.

The World's Oil Supply

Although oil is found in many places, most of it is concentrated in four large regions, all near inland seas. By far the most important oil region is the Middle

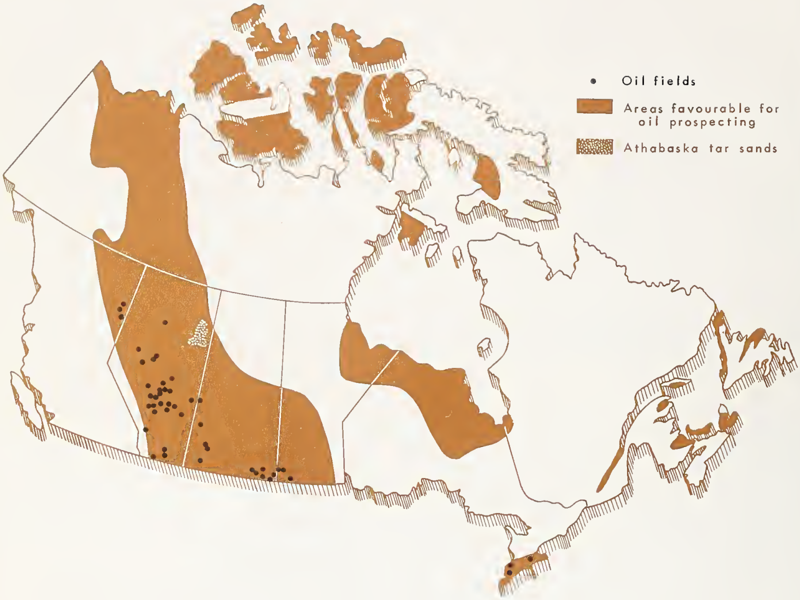


Fig. 13-1. Oil fields in Canada.

East, stretching from the eastern end of the Mediterranean to Pakistan. Almost 70 per cent of the world's oil reserves lie in this region, which includes Iran, Iraq, Arabia, and southwestern Russia. A second region lies around the Caribbean Sea and the Gulf of Mexico. It includes Mexico, Venezuela, Colombia, and the states of Texas and New Mexico. A third region is in Canada. A fourth, less important region is situated in the islands of Java and Sumatra in the East Indies, and the Malay States, and Burma.

Oil in Canada

The first oil well was drilled in Canada in 1858, just one year before the first oil well was drilled in the United States. This was in Bothwell, Ontario, and the oil was used as the fuel in lamps and stoves. From this small beginning a century ago some of the largest industries in Canada have developed. At first oil was found only in the eastern provinces of Ontario and New Brunswick and then, in 1947, oil was discovered at Leduc, Alberta. Many new oil fields have now been discovered in Alberta, Manitoba, Saskatchewan, and British Columbia. It is not surprising that, since the discovery of oil, the economic life of the prairie provinces has changed.

Canada also has huge reserves of oil in the Athabaska tar sands. So far oil has not been extracted on a large scale from the tar sands because it is cheaper to obtain oil from wells. However, a great deal of research is being done to find a cheap method of extracting oil from the sands, and a pilot plant for this purpose has already been built in northern Alberta. As the oil fields become depleted, it will be economically possible to turn to these vast reserves in Athabaska.

The Location of Oil

To locate oil is a difficult problem. A thorough examination of the land is made before drilling begins. Geologists, physicists, and engineers investigate the area, but even favorable reports of scientists do not insure success. In fact, at least 50 per cent of drilled wells are dry; that is, they do not yield oil.

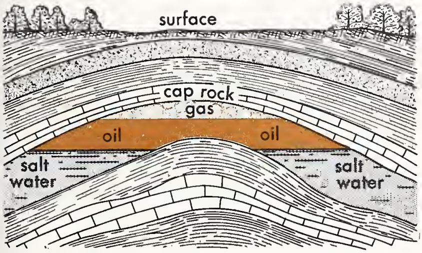


Fig. 13-2. Oil may be trapped by a dome of hard limestone.

It is generally believed that oil originates in marine plant and animal life. One source of oil is probably diatoms, which are microscopic plants. The living plants contain droplets of oil which are carried to the sea floor when the diatoms die. Another source is probably fish, which yield oil when decomposed.

Before oil can accumulate in rock formations far below the sea floor, it must be trapped against an obstruction. Otherwise it would remain as a thin layer spread over a wide area. A geological formation that favors oil accumulation is shown in Fig. 13-2. Sandstone rock, once the floor of an ancient sea, is folded into a dome. The oil deposits then flow under pressure and a cap rock of impervious limestone traps it in the dome. Notice that gas accumulates above the oil, and sea water below it. Is this to be expected? Still another oil trap can be caused by a fault, as shown in Fig. 13-3.

The geologist's problem is to locate these "pools" of oil thousands of feet below the surface. How does he proceed? First he examines the surface rocks, noticing the dip of the beds and looking particularly for outcrops of hard limestone which is a common caprock. He gets more information on the nature and age of the rocks near the surface by drilling and examining rock cores brought to the surface by the drilling machine. The kinds of fossils in cores are particularly significant. If conditions appear favorable, a physicist takes over and investigates further with a seismograph. To do this, a charge of dynamite is buried near the surface and exploded. Vibrations from the explosion travel through the rocks and, if they strike a hard

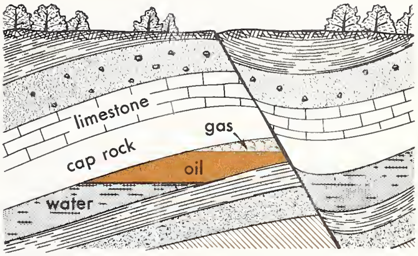


Fig. 13-3. Oil may be trapped by a fault.

Fig. 13-4. A dynamite explosion helps to locate oil.

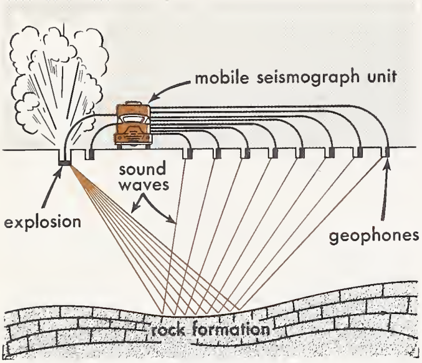


Fig. 13-5. Vibrations from the explosion are reflected from cap rock, picked up by microphones, and recorded on a film.

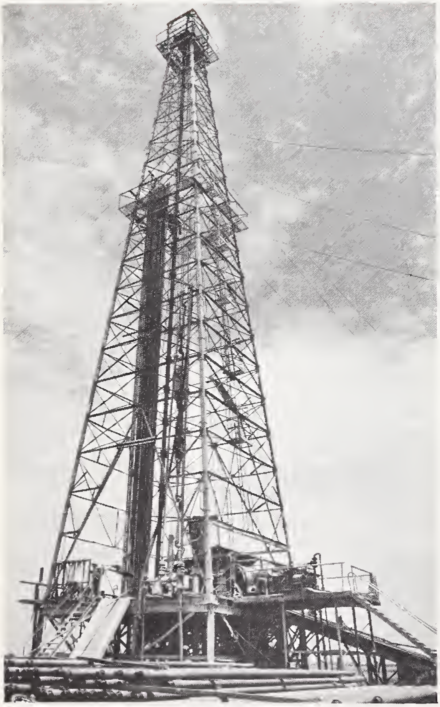


Fig. 13-6. A derrick. The lengths of drill pipe stacked in the derrick are lowered into the bore hole.

cap rock below the surface, they are reflected back to the surface. Here they are registered by microphones and recorded on a film. From the readings obtained in this way, it is possible to compute the depth of the reflecting surface. If all indications are favorable, drilling begins.

Drilling for Oil

Drilling is a long and expensive operation. First, a derrick—a steel structure about 200 feet tall—is erected for handling equipment. A rotating bit at the end of a shaft cuts through rock, just as a carpenter's drill bores through wood. The speed of drilling depends on the nature of the rock. Through hard rock the distance may be only a few feet a day; through soft rock it may be more than 100 feet. Drilling deep wells, which may be three miles in depth, may take from 9 to 12 months. Samples of rock are constantly brought to the surface and examined for traces of oil. When oil is struck the drill is removed and replaced by a "Christmas tree" which is a complicated arrangement of valves, pipes and gauges to control the flow of oil. The cost of drilling a well may be anywhere from $50,000 to $500,000, the average being about $200,000.

The life of a pool may vary from one to twenty years or so. The average daily yield per well is about 10 barrels, or 450 gallons.

Separation of Crude Oil into Fractions

Crude oil, or petroleum as it is sometimes called, is a thick dark-colored liquid. It is of little use in its raw state; before it can be used to drive a car, heat a house, or lubricate machinery, it must be separated into useful fractions. This is done by distillation at a refinery.

Oil from the wells is piped to storage tanks in the oil field. From the storage tanks it is carried to refineries which may be more than a thousand miles away. As is shown on the map (Fig. 13-8) a pipeline carries crude oil from the Alberta oil fields across the Rocky Mountains to refineries in Vancouver.

At a refinery, crude oil is heated in a boiler and the hot oil vapors enter the bottom of a tower like that shown in Fig. 13-9, where they begin to condense to a liquid. The tower is hottest at the bottom and coolest at the top. Therefore, the vapors that are easiest to condense (those that condense at the highest temperatures) change to a liquid near the bottom of the tower, and the vapors most difficult to condense (those that condense at the lowest temperatures) liquefy near the top. As the vapors liquefy they are collected on "trays" at various levels and run out of the tower through outlet tubes. There are actually five trays and therefore five outlets to carry away the various fractions, as they are called. As shown in Fig. 13-9, the uppermost outlet tube carries off gasoline; the next, kerosene; the next, fuel oil; the next, lubricating oil; and the lowest, vaseline and paraffin wax.

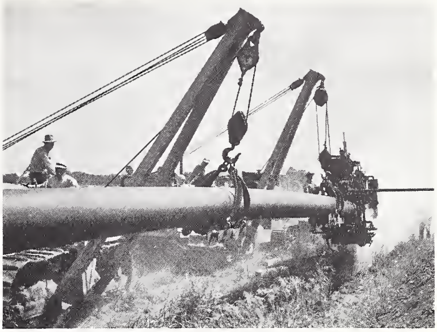


Fig. 13-7. When the pipeline is buried in the trench, it will carry a steady stream of oil to a distant refinery.

Oil Fractions

The molecules of all the oil fractions are ***hydrocarbons***; that is, they consist only of atoms of hydrogen and carbon. Each fraction contains many different kinds of hydrocarbon molecules.

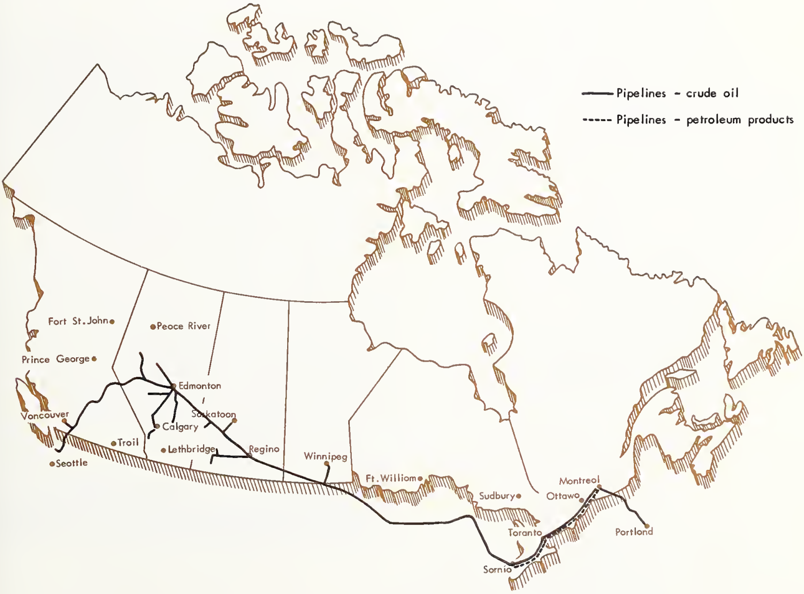


Fig. 13-8. Map of pipelines in Canada.

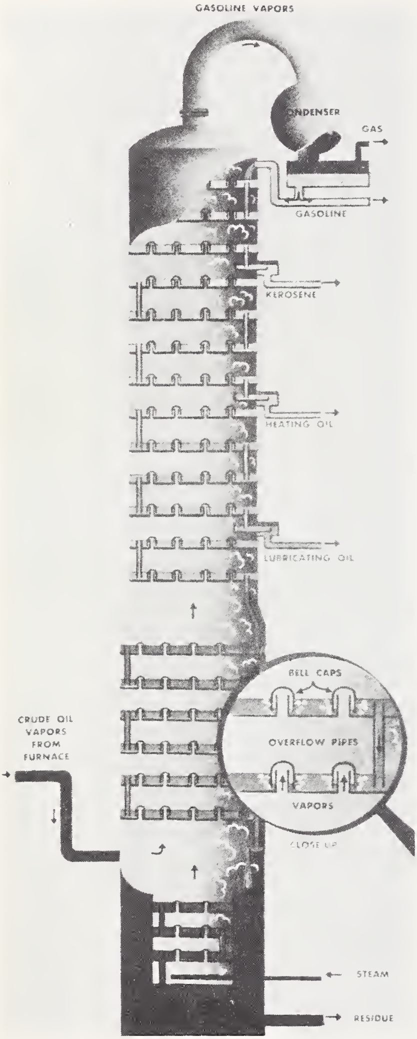


Fig. 13-9. A fractionating tower. The highest boiling fraction condenses near the bottom of the tower; the lowest boiling fraction condenses near the top.

The molecules of gasoline are smaller than the molecules in the other fractions. For this reason gasoline vaporizes easily and, as you know, it is a fuel suitable for the internal combustion engines of automobiles and airplanes. One of the molecules of gasoline is C_6H_{14}.

Kerosene molecules are larger than gasoline molecules. They do not vaporize as easily as gasoline molecules and are a good fuel for jet engines. The molecules of fuel oil are still larger; they are a suitable fuel for household furnaces and diesel engines. The molecules of lubricating oil are so large that, at ordinary temperatures, they hardly evaporate at all. And, as you know, the important use of lubricating oil is to reduce friction in machinery. The various fractions of crude oil are summarized in the table on page 127.

What is Octane Number?

Gasoline is a mixture of several compounds, all hydrocarbons. These include pentane (C_5H_{12}), hexane (C_6H_{14}), heptane (C_7H_{16}), and octane (C_8H_{18}). In the cylinder of an automobile engine all these compounds burn to form carbon dioxide

Fig. 13-10. An oil refinery. The tall tower on the right is a fractionating tower.

Name of fraction	Condensation temperature	Uses of fraction
1. Gasoline	About 150°F	Fuel for automobiles and planes
2. Kerosene	About 300°F	Illuminant; fuel for stoves and jet planes
3. Fuel oil	About 500°F	Fuel for furnaces and diesels
4. Lubricating oil	About 600°F	Lubricants
5. Vaseline and paraffin wax	About 700°F	Ointments and candles
6. Asphalt and tar	Residue	Road construction and roofing

and water. Or, in symbols,

$$\left.\begin{array}{l} C_5H_{12} \\ C_6H_{14} \\ C_7H_{16} \\ C_8H_{18} \end{array}\right\} + O_2 \rightarrow CO_2 + H_2O + \text{heat}$$

The heat released in these reactions causes the carbon dioxide and water vapor to expand and, in expanding, these gases force the piston down the cylinder. To perform efficiently, the hydrocarbon vapors ought to begin to burn the instant the piston reaches the top of the cylinder. But some of them burn faster than others. Heptane, for example, begins to burn too early, before the piston has reached the top of its stroke. This causes gases to expand at the wrong time which, in turn, produces a hammer-like blow, called a "knock" on the piston. A knock causes the engine to lose power. Octane, on the other hand, burns at the right rate at the right time. It produces little or no knock in the engine; we can say that its antiknock value is high.

To measure these differences in antiknock value, an octane number scale has been devised on which octane is given a rating of 100 and heptane a rating of zero. For instance, if a sample of gasoline has an octane number of 80, its "knock" is the same as would be given by a mixture of 80 per cent octane and 20 per cent heptane. The octane number corresponds to the percentage of octane in an octane-heptane mixture.

Ordinary gasoline has an octane number of about 75 and high-test gasoline about 85. Some aviation gasolines have octane numbers of over 100, which means that their antiknock properties are better than those of octane.

The octane number of gasoline can be increased by adding a substance called tetraethyl lead. A gasoline that contains this ingredient is called ***ethyl gasoline***. Tetraethyl lead is highly poisonous. However, very little of it is needed in gasoline; even one part of tetraethyl lead in 1000 parts of gasoline greatly improves the octane rating of the fuel.

Natural Gas

Natural gas is almost always present in oil fields. Indeed, it is the pressure exerted by natural gas that forces oil to the surface. Most of the natural gas, however, is obtained in regions where there is little oil—from gas wells rather than oil wells.

Drilling for gas is a similar process to drilling for oil. A derrick is erected, a well is sunk, and, when gas sand is tapped, the gas rushes up the pipes. Its flow is controlled by valves. As gas escapes, the internal pressure diminishes until, eventually, no more comes to the surface. The well is then dry. Gas fields are shown in Fig. 12-1.

Natural gas is a mixture of hydrocarbons, mainly methane, or CH_4 (about 85 per cent), and ethane, or C_2H_6 (about 10 per cent). It burns with a hot blue flame, giving considerably more heat than coal gas. One cubic foot of natural gas will bake a pie; 60 cubic feet of it will bake 100 pounds of bread. It is by far the most important fuel gas in industry.

Natural gas was discovered in Alberta as early as 1893 and, like crude oil, it is now found in British Columbia, Saskatchewan, New Brunswick, and Ontario as well as Alberta. As is the case with crude oil, natural gas is carried by pipelines to centers of industry. The map below shows the network of pipelines that carry natural gas.

Coal, Petroleum, and Natural Gas

The petroleum industry, once concerned entirely with producing gasoline, kerosene, fuel and lubricating oils, has, like the coal industry, turned to the production of chemicals. Nevertheless, coal, petroleum, and natural gas are still important fuels and are likely to remain so until atomic energy becomes cheaper than the energy of coal, or until scientists learn how to trap and store energy from the sun efficiently and cheaply.

At the present time, about 40 per cent of the heat energy used in Canada is supplied by petroleum, about 34 per cent by coal, about 22 per cent by natural gas, and the rest (about 4 per cent) by water power.

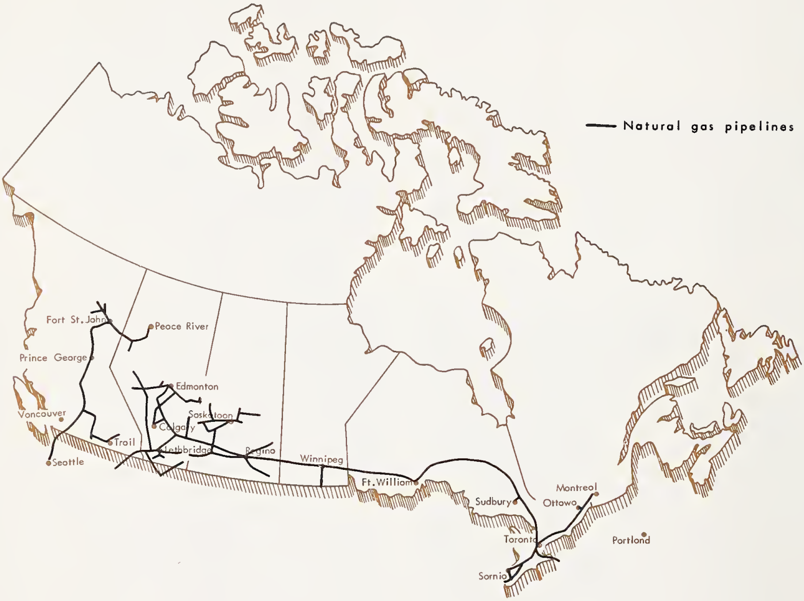


Fig. 13-11. Natural gas pipelines.

Things to Remember

The *first oil well* on the North American continent was drilled in Ontario in 1858.

The *principal source of oil* is probably diatoms, microscopic plants that live in the seas.

The *useful fractions* obtained from crude oil are [**1**] gasoline, [**2**] kerosene, [**3**] fuel oil, [**4**] lubricating oil, [**5**] vaseline and paraffin wax, [**6**] asphalt and tar.

A *hydrocarbon* is a compound of hydrogen and carbon.

Gasoline is a mixture of hydrocarbons which include pentane, hexane, heptane, and octane.

Natural gas is mainly a mixture of methane (about 85 per cent) and ethane (about 10 per cent).

Questions

Part A

1. What is meant by a "pool" of oil?
2. What is a derrick and what is it used for?
3. What is crude oil?
4. Name the useful fractions obtained from crude oil.
5. What is a hydrocarbon? Give an example from [**a**] gasoline, [**b**] natural gas.
6. Name four of the constituents of gasoline and give their chemical formulas.
7. Ordinary gasoline has an octane number of about 75. What does this mean?
8. What is ethyl gasoline?
9. What is the approximate composition of natural gas?

Part B

10. Discuss briefly the main locations of oil and natural gas in Canada.
11. How is crude oil separated into useful fractions?
12. What happens when gasoline is exploded in the cylinder of a gasoline engine? Write an equation for this reaction.
13. Explain the energy transformations that take place in the cylinder of an automobile engine.
14. What causes the knock in an automobile engine?
15. Natural gas is a fuel gas. [**a**] What does this statement mean? [**b**] Write two equations to show what happens when natural gas burns.

14

Carbon Dioxide

In Chapters 12 and 13 you learned that carbon dioxide is usually formed in the burning process, and in Chapter 11 you learned that carbon dioxide is used to extinguish fires. But so far we have not prepared and collected carbon dioxide. How can this be done? A simple way to prepare it is to pour an acid on baking soda (sodium bicarbonate). Any of the mineral acids will do, but vinegar is also satisfactory. You may know that carbon dioxide is much denser than air. For this reason, it can be collected by displacing air. This is more convenient than displacing water which was necessary when we prepared oxygen.

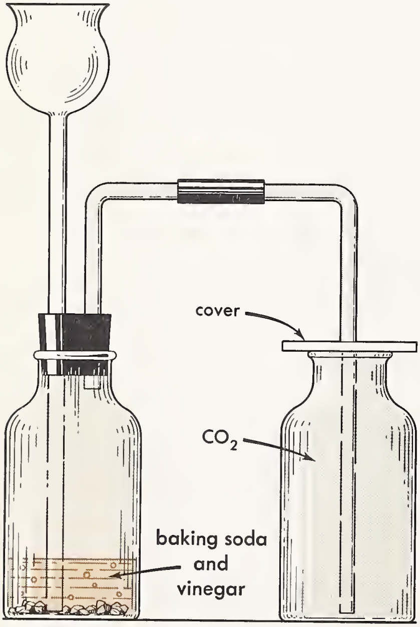


Fig. 14-1. Carbon dioxide is prepared by pouring vinegar onto baking soda.

Experiment

14-1. To prepare carbon dioxide

Cover the bottom of a bottle with baking soda. Force a thistle tube and a right angle bend through the holes of a 2-hole stopper and then set up the apparatus as shown in Fig. 14-1. Pour some vinegar down the thistle tube. A vigorous reaction takes place, and carbon dioxide displaces air in the bottle. Hold a burning taper near the mouth of the bottle. If the taper is extinguished, the bottle is filled with carbon dioxide. Put a glass cover on the bottle and save the carbon dioxide for a later experiment.

It may be necessary to add more baking soda to the bottle before proceeding with the experiment. Half fill a test tube with water and place a few pieces of blue litmus paper in the water. Now lead the escaping carbon dioxide into the water and observe that the litmus paper slowly turns red.

Now replace the test tube of water by a test tube containing limewater. Notice that the limewater turns milky as the gas bubbles through it.

We have made a number of observations in this experiment that need some explanation. First, what is litmus and what is it used for? Litmus is a vegetable dye that changes color in an acid solution; it changes from blue to red. For example, a piece of blue litmus paper instantly turns red if it is dipped into vinegar. In other words, ***the turning of blue litmus paper to red constitutes a simple test for an acid.***

Carbon dioxide reacts with water to form an acid. As carbon dioxide bubbled through the water, the blue litmus turned red. Therefore we conclude that an acid is formed. What is the acid? The acid is carbonic acid (H_2CO_3) and although it is much weaker than mineral acids, carbonic acid, as we shall see, plays an important part in various geological processes. The chemical reaction is

water + carbon dioxide → carbonic acid

or, in symbols,

$$H_2O + CO_2 \rightarrow H_2CO_3$$

Carbon dioxide turns limewater milky. If lime (or calcium oxide) is shaken with water it reacts with water to form a white solid called calcium hydroxide. Or,

calcium oxide + water → calcium hydroxide

and, in symbols,

$$CaO + H_2O \rightarrow Ca(OH)_2$$

Calcium hydroxide is not very soluble and only a small proportion of it dissolves in water. This dilute solution is called ***limewater.***

Carbon dioxide reacts chemically with limewater to form calcium carbonate (sometimes called chalk). Calcium carbonate is almost insoluble in water; that is why it appears as a fine milky precipitate. The reaction is

limewater + carbon dioxide → calcium carbonate + water

or, in symbols,

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Carbon dioxide can be poured like water. We have already stated that carbon dioxide is denser than air and that it smothers a flame. These two properties are shown in the following experiment.

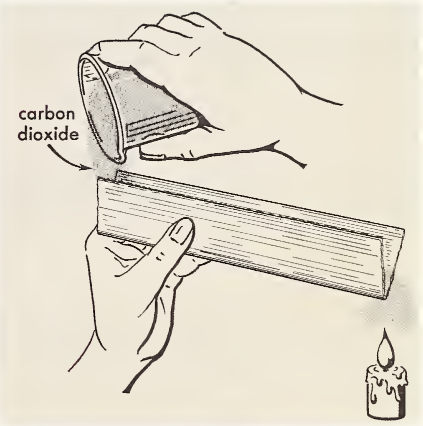


Fig. 14-2. Carbon dioxide poured down the trough extinguishes a candle flame.

Experiment

14-2. To pour carbon dioxide onto a candle flame

Hold the groove of a paper hand towel so that its lower end is near a candle flame. Remove the cover from the bottle of carbon dioxide and pour the gas down the trough of the paper towel, as shown in Fig. 14-2. The candle flame is extinguished as soon as the carbon dioxide covers it.

This experiment gives two clues as to why carbon dioxide is such a good fire extinguisher. One reason is that carbon dioxide displaces air and deprives a burning object of essential oxygen. Another reason is that carbon dioxide is itself incombustible. The carbon atoms in carbon dioxide (CO_2) have already combined with as much oxygen as they can hold. They cannot, therefore, combine with more oxygen. If the carbon atoms in carbon dioxide *could* combine with oxygen, carbon dioxide could not be used as a fire extinguisher. Why not?

Respiration

The combustion of such fuels as coal, gasoline, and natural gas, causes millions of tons of carbon dioxide to enter the air every day. Combustion is not the only process, however, that increases the carbon dioxide content of the air. The respiration of both plants and animals does the same thing. A man, for example, exhales about 500 cubic centimeters of air at every breath; of this air, 20 cubic centimeters are carbon dioxide.

Respiration is the slow oxidation of compounds from food in the cells of the body with the release of carbon dioxide, water, and heat energy. Like an engine, an animal needs fuel to do work. The fuel of an engine may be coal or gasoline; the fuel of an animal is the carbon compounds in food.

The food we eat enters the alimentary canal, where digestive juices break it down into substances that can pass through the membrane of the intestine and into the blood vessels. Once in the blood stream, these substances are carried to cells in all parts of the body.

As stated in an earlier chapter, the membrane that covers the lungs allows the oxygen of the air to enter the blood stream. This oxygen is carried to the cells, where it oxidizes the digested food particles, forming carbon dioxide and water and releasing energy. The carbon dioxide passes from the cells to the blood stream, then through the membrane of the lungs, where it is exhaled. Thus ***respiration is an oxidation process that takes place in the cells of the body.***

The fact that exhaled air contains more carbon dioxide than inhaled air can be verified by the following experiment.

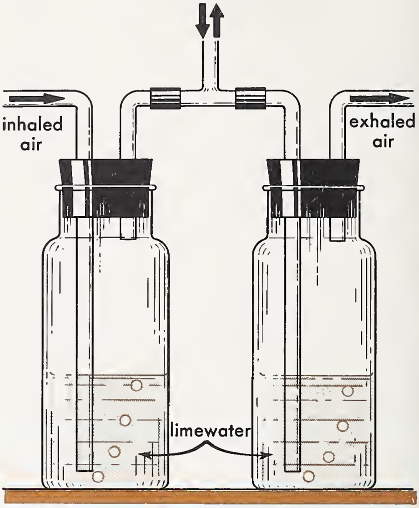


Fig. 14-3. Exhaled air forms a white precipitate when bubbled through limewater.

Experiment

14-3. To compare the carbon dioxide in ordinary air with that in exhaled air

Arrange two bottles containing limewater as shown in Fig. 14-3. The inlet and outlet tubes are so arranged that, when the T-tube is in the mouth, air can be drawn in through the left-hand bottle and expelled through the right-hand bottle. With the T-tube in the mouth, inhale and exhale about ten times.

The slight milkiness that forms in the left-hand bottle proves that carbon dioxide is present in the air. Why? The heavy white insoluble substance in the right-hand bottle shows that exhaled air contains a much higher percentage of carbon dioxide than inhaled air.

Carbon Dioxide in the Air

If the two processes of combustion and respiration were not counterbalanced by other processes in nature, the atmosphere would eventually contain so much carbon dioxide that it would be unable to support life. Human beings can live drowsily in an atmosphere containing 5 per cent carbon dioxide, but they would die if this were increased to 10 per cent. The atmosphere actually contains very little carbon dioxide, about 0.04 per cent, or 4 parts of carbon dioxide in 10,000 parts of air. The carbon dioxide content of the air is fairly constant. The processes that absorb carbon dioxide must therefore balance the processes that produce it. The absorbing processes are ***photosynthesis*** and ***solubility.***

What is Photosynthesis?

All vegetation is made up of carbon compounds, mostly as cellulose but some as sugar and starch. Starch, for example, is the main constituent of corn, wheat, and potatoes; cellulose is the woody material in every plant or tree; cotton, too, is almost pure cellulose. Where does the carbon come from? Certainly not from the soil. ***All the carbon in vegetation comes from the carbon dioxide of the air.*** Carbon from carbon dioxide is combined with hydrogen and oxygen to form these compounds. Chlorophyll, the green "blood" of leaves, stalks and grass, plays a part and so does sunlight. That is why the process is called ***photosynthesis,*** a word derived from Greek *photo,* meaning "by means of light" and *sunthesis,* meaning "composition."

The photosynthesis reaction may be expressed as follows:

carbon dioxide + water →
cellulose or starch or sugar + oxygen

If we selected the simplest sugar, glucose, $C_6H_{12}O_6$, the symbolized equation is

$$CO_2 + H_2O \rightarrow C_6H_{12}O_6 + O_2$$

That is to say, water molecules are taken up through the roots, and carbon dioxide molecules are inhaled through the pores in the leaves. The plant then reshuffles the atoms of these compounds in a manner not yet completely understood, to form carbohydrates which are the most basic of all foods. ***Carbohydrates*** is a general term that applies to sugars, starch, and cellulose; they are compounds of carbon, hydrogen, and oxygen. Notice particularly that in the photosynthesis reaction the surplus oxygen is released and so replenishes the air with oxygen for plants and animals to breathe.

How are carbohydrates formed? Nature manages to make carbon dioxide and water combine, to form carbohydrates in a way that is still a mystery, even though more than 70 years of scientific research have been spent on the problem. It is known that the energy of sunlight activates this reaction, and that chlorophyll in some way acts as a catalyst.

Photosynthesis is the most vital of all chemical reactions; if this process of nature were to stop, the world would soon starve to death. That is why scientists will continue to work on this problem until they have solved it. Indeed, some new techniques with radioactive carbon are very promising and there is hope that, in the near future, scientists will be able to imitate nature's photosynthesis reaction. Once this is accomplished it will be possible to harness the sun's energy, thus providing fuels for those nations without natural resources. And even more important, it will be possible to make synthetic foods out of carbon dioxide, water, and the sun's energy. This would indeed be a historic development; it would provide food for the world's growing population and go a long way toward solving the world food shortage.

The green substance called chlorophyll is made up of highly complex molecules which nature can manufacture without difficulty. It is quite easy to extract chlorophyll from green leaves with alcohol as the following experiment shows.

Experiment

14-4. To extract chlorophyll from green leaves

Place a green leaf (preferably a geranium leaf) in a flask. Pour a little methyl alcohol (wood alcohol) over the leaf and heat the flask with hot water, not with a flame. Close the flask with a stopper and shake it. Notice that the alcohol turns green because chlorophyll has dissolved in it, and the leaf loses its green color.

Photosynthesis and Combustion

Thus it is that, in plants, two operations –photosynthesis and respiration–take place at the same time. Moreover, one is the reverse of the other. In photosynthesis, carbohydrates are built up; in respiration, carbohydrates are broken down. These processes are not balanced, however, because in sunlight photosynthesis takes place on a much larger scale than respiration.

Similarly, photosynthesis is the reverse of combustion. *In photosynthesis carbon dioxide is used up and oxygen released; in combustion oxygen is used up and carbon dioxide released. In photosynthesis light energy is taken in; in combustion heat energy is given out.*

The Solubility Effect

Carbon dioxide is also constantly removed from air by the dissolving action of large bodies of water. Carbon dioxide reacts with water to form carbonic acid, which slowly dissolves such rocks as limestone and chalk.

The calcium salt in solution is carried to the sea where shellfish use it to make hard shells of calcium carbonate. But this is not the end of the chain. When shellfish die, their shells collect on the floor of the ocean. Here they are compressed and cemented together, and eventually they may be raised above sea level to form a mountain of chalk or limestone.

The Carbon Dioxide Cycle

It is now apparent that in the processes of photosynthesis, combustion, respiration, and solubility, carbon dioxide takes part in a cycle of operations. Starting from air and tracing the carbon dioxide over a long period of time, we see that it can engage in

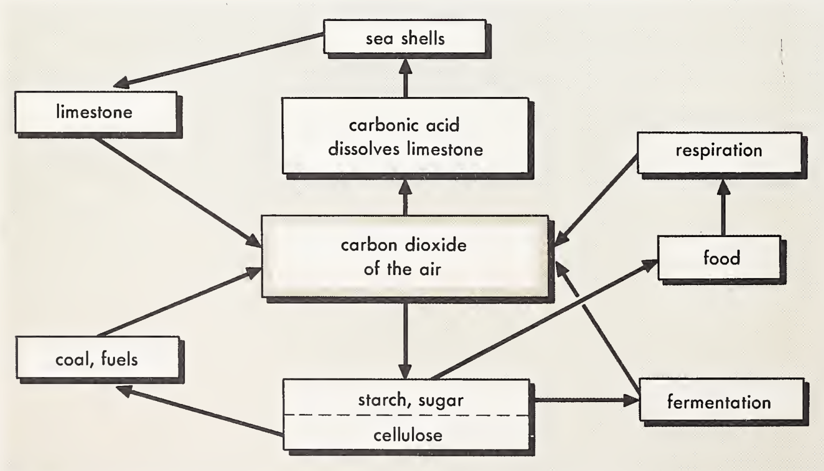


Fig. 14-4. The carbon dioxide cycle.

various activities. It might enter a starch molecule during photosynthesis; if the starch is digested by an animal, it would be released during respiration. It could then dissolve in water and eventually become part of the shell of an animal. Then, for ages, it might be trapped as limestone in a mountain. If limestone is heated in a kiln (a tall oven) to make lime, carbon dioxide is released so that our molecule is again available for another series of operations. Fig. 14-4 shows other journeys that the molecule might make. This continuous circulation in nature is called the ***carbon dioxide cycle.***

Carbon Dioxide and Weather

The amount of carbon dioxide that enters the atmosphere from burning coal, oil, and natural gas has steadily increased since the Industrial Revolution. At the present time about ten billion (10,000,000,000) tons of carbon dioxide are released into the air every year as a result of man's various industrial activities. This is more than photosynthesis can cope with, and scientists have computed that, if combustion continues at the present rate, the amount of carbon dioxide in the air will be doubled in a century or so. Will this have any noticeable effect on our way of life?

The accumulating carbon dioxide forms a sort of invisible veil over the earth's surface. The heat radiation from the sun, which comes in short waves, is able to penetrate this veil. Heat radiation from the ground, however, escapes in the form of long waves which cannot easily escape through the carbon dioxide layer. In other words, the veil behaves like the glass frame of a greenhouse. The increasing amount of carbon dioxide traps more heat near the earth's surface and tends to make the climate warmer. The average rise in temperature, as computed by meteorologists, is not very great–only about 1.5 degrees per century. Nevertheless, this could be a considerable factor if the accumulation of carbon dioxide continued through centuries of time.

Indeed, a decrease of the carbon dioxide in the air is one of the theories to account for the ice ages. The ice ages were preceded by millions of years of mountain building. This was followed by the weathering of vast surfaces of exposed igneous rock, which may have greatly reduced the amount of carbon dioxide in the air. A decrease in the carbon dioxide would result in a colder climate, so that glaciers could result.

As the mountains were leveled, the weathering process slowed down. Volcanic eruptions then took place and carbon dioxide escaped into the atmosphere from inside the earth. As a result, the climate became warmer and the glaciers receded.

Things to Remember

Any acid will turn *blue litmus* paper red.

Carbonic acid is formed if carbon dioxide dissolves in water.

Carbon dioxide turns *limewater* milky.

Respiration is an oxidation process that takes place in the cells of the body.

During respiration, carbon dioxide (and other gases) are exhaled.

The *amount of carbon dioxide in air* is about 0.04 per cent (4 parts in 10,000 parts of air).

In *photosynthesis* carbon dioxide is used up, oxygen is released, and energy stored.

Photosynthesis and combustion are reverse operations.

Sugar and starch are examples of *carbohydrates.*

The *carbon dioxide content of air is increased* by combustion and respiration, but *decreased* by photosynthesis and solubility in water.

The circulation of carbon dioxide in nature is called the *carbon dioxide cycle.*

Questions

Part A

1. [**a**] What is the limewater test for carbon dioxide?
   [**b**] What is the insoluble substance formed in this test?
2. What is litmus and what is it used for?
3. What is the meaning of the terms *digestion* and *respiration*?
4. What is the percentage of carbon dioxide in [**a**] atmospheric air, [**b**] exhaled air?
5. What is chlorophyll? What is its use?
6. What is a carbohydrate? Give two examples.
7. Name the factors which tend to increase the carbon dioxide content of the air, and those which tend to reduce it

Part B

8. Draw and label a diagram to show how carbon dioxide can be prepared.
9. Explain what happens when carbon dioxide is bubbled through water. Write an equation for the reaction.
10. Explain what happens when carbon dioxide is bubbled through limewater. Write an equation for the reaction.
11. What are the two properties of carbon dioxide that make it useful as a fire extinguisher? Explain.
12. What is photosynthesis? Give an example.
13. Operation of the photosynthesis reaction by scientists would be a historic landmark in the history of civilization. Explain why.
14. Compare and contrast combustion and photosynthesis.
15. What is the carbon dioxide cycle? Explain.

Things to Do

Photosynthesis of starch

Shield two or three leaves of a potted geranium from light by an envelope of black paper. (The black paper used to wrap photographic paper is satisfactory for this purpose.) The black wrapping should be put in place during the afternoon of one day and the plant left to grow in the light during the next day.

During the afternoon of the second day cut from the plant a leaf that has been exposed to light and also one that has been wrapped in black paper. Drop the leaves into hot water and leave them for about five minutes.

Now place the two leaves in separate Petri dishes. Spread them out gently, being careful not to tear them. Cover them with alcohol to extract the chlorophyll. After the chlorophyll is extracted, both leaves are completely discolored, and, judged by outward appearances, they look alike. The following chemical test, however, will distinguish between them.

A drop of tincture of iodine turns a starch solution blue; tincture of iodine can therefore be used to indicate the presence of starch. Leaving only a small quantity of alcohol in each Petri dish, add from two to four drops of iodine tincture and mix well by rocking the dishes. A dark-blue color develops rapidly in the leaf that has been exposed to light but not in the leaf that has been kept in the dark. What conclusion can you draw from this experiment?

This operation should be repeated on the afternoon of the third day to confirm this result.

UNIT

IV

Heat and Temperature

15

Effects of Heat

One of the most familiar effects of heat is the expansion of mercury in a thermometer. Do all liquids expand when they are heated? And do solids expand with heat? And gases also? Let us do some experiments to help us answer these questions. We will begin with solids.

Experiment

15-1. To show that solids expand when heated and contract when cooled

Lay a piece of copper tubing, at least 2 feet long, on a table. Fix one end of it by a clamp to the table. Attach a piece of

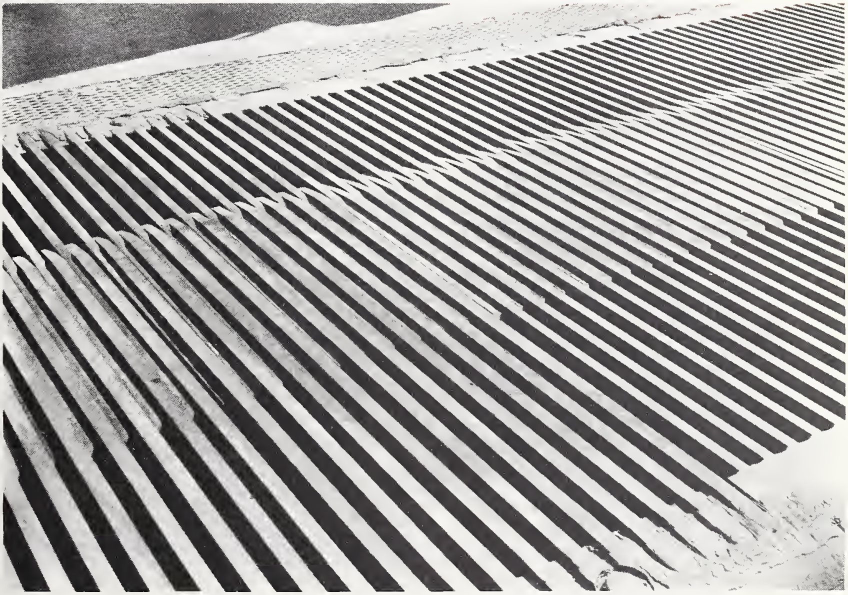


Fig. 15-1. This photograph shows the roadway expansion joints on a bridge.

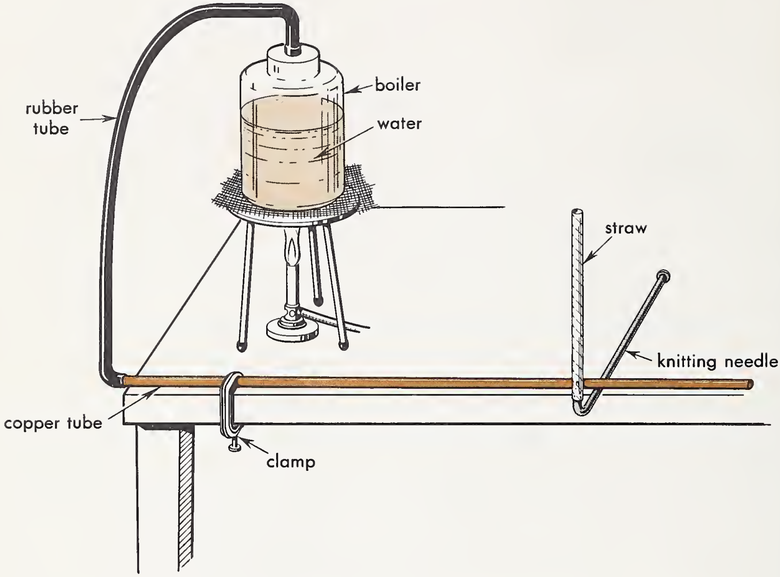


Fig. 15-2. The rotation of the knitting needle indicates expansion of the copper tube.

rubber tubing to this end and to a boiler. Bend one end of a knitting needle or a piece of coat-hanger wire through a right angle and then fasten a straw to the short arm of the knitting needle by Scotch tape. Place the knitting needle under the free end of the tube with the straw in a vertical position. The arrangement is shown in Fig. 15-2.

Heat water in the boiler until steam issues through the tube. Observe that the straw turns through an angle of about 30 degrees. What does this indicate? Now remove the burner, thus allowing the tube to cool. Notice that the straw slowly returns to its vertical position. What does this indicate?

Now place the needle about midway along the length of the tube and again pass steam through the tube. Notice that the straw turns through a smaller angle than before, about 15 degrees or so. What does this indicate?

Now replace the copper tube by an aluminum tube and then by a glass tube. Again observe the angles of rotation of the straw when steam is passed through the tube. What do these observations indicate?

Since the needle acts as a roller, it is apparent that copper expands when heated and contracts when cooled. And since the angle of rotation was smaller at the halfway mark than when the needle was near the end of the tube, we can conclude that the longer the tube, the greater is the total expansion.

It could also be observed that the rotation produced by the aluminum tube was somewhat greater than for copper, and that the rotation produced by the glass tube was considerably less than that produced by the copper tube. We therefore conclude that the amount of expansion depends upon the kind of material. If the above tubes (or rods) of equal lengths are heated through the same temperature, it is apparent that, of these three substances, aluminum has the greatest rate of expansion and glass the least.

Some Familiar Examples of Expansion

You have probably noticed that concrete highways are laid in sections and that between the sections there are spaces in which a soft filler like asphalt has been poured. Why are concrete highways laid in sections? The spaces are expansion joints; if there was no room for the concrete to expand the road surface would buckle when heated by the summer sun. You may already know that one of the causes of weathering of rocks is the repeated expansion and contraction of rock surfaces.

Since expansion and contraction are results of temperature changes, there are many examples of it. Steel bridges, for instance, are also built in sections, and each section is mounted on rollers as shown in Fig. 15-3. The expansion joints are finger-like projections which interlock and so prevent a gap in the roadbed during contraction in winter. Although the actual expansion of a foot of steel is exceedingly small, the total change in the length of a bridge between winter and summer temperatures can be considerable. For example, the Golden Gate Bridge in San Francisco, which is 4200 feet long, changes in length by almost 3 feet.

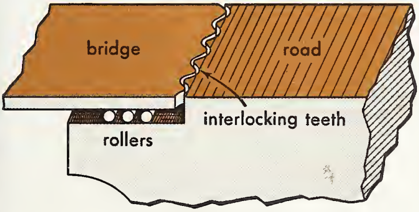


Fig. 15-3. The sections of steel bridges are mounted on rollers to allow for expansion.

Steam pipes also have expansion joints, otherwise the strain produced at high temperatures would cause leaks in the pipe. In industrial plants the long steam pipes between buildings are usually above ground, and the expansion is allowed for by such a simple device as a loop in the pipe (see Fig. 15-4). As the pipe becomes longer or shorter the loop readily bends and changes shape and, in this way, dangerous strains in the pipe are prevented.

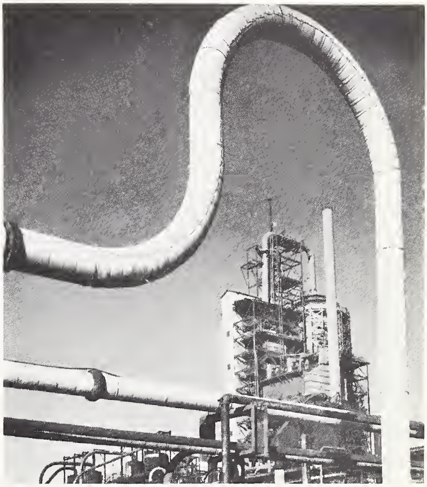


Fig. 15-4. The loop in a long steampipe changes shape, thereby allowing for the expansion of the pipe.

Glass also expands when heated, although its expansion is even less than that of steel. We know by experience that if hot water is poured into a thick glass jar, the jar is likely to crack. Why is this? The hot water causes the inside of the jar to expand. The outside, however, does not expand for some time because heat is not readily conducted through glass. A strain is therefore set up between the inner and outer surfaces and this may cause the glass to break.

The strain could be diminished by making the jar of very thin glass (why?), but this would make the glass fragile. To meet this difficulty a special kind of glass, called "pyrex," was developed. The expansion of pyrex is only about one-fourth that of ordinary glass. As a result, the small change in size between the two surfaces, that results from a sudden change in temperature, is not enough to crack it. For this reason, pyrex cooking dishes can be made much thicker than those of ordinary glass and therefore more durable.

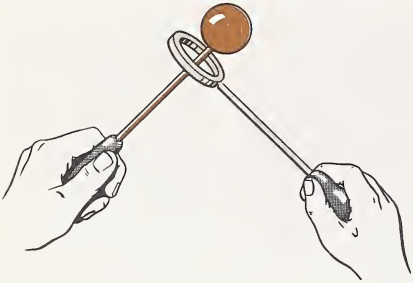


Fig. 15-5. Does the hole become larger or smaller when the ring is heated?

A Ball and Ring

A metal ball and ring are shown in Fig. 15-5. At ordinary temperatures, the ring is just large enough to allow the ball to pass through it. If the ring is heated in a Bunsen flame will the hole get larger or smaller? As the ring expands both inner and outer circumferences of the ring must get larger; therefore, the hole must become larger. We can check our reasoning by doing an experiment with the ball and ring. Or we can substitute a screw and screw eye for the ball and ring.

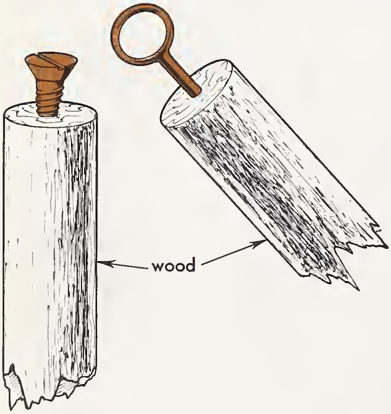


Fig. 15-6. The screw just passes through the screw eye at ordinary temperatures.

Experiment

15-2. The hole of a screw eye becomes larger when the eye is heated

Fasten a screw eye into the end of a strip of wood about a foot long. Select a screw with a head just a little too large to pass through the eye. File the edge of the screw until it is just small enough to pass through the screw eye. Now fasten the screw to another strip of wood also about a foot long. When the screw and screw eye are in place, about an inch should protrude above the ends of the sticks as shown in Fig. 15-6.

Heat the head of the screw in a Bunsen flame and observe that it soon becomes too big to pass through the eye. Cool the screw by immersing it in a beaker of water.

Now heat the screw and eye together, and observe that the screw passes through the eye at all temperatures, thus proving that the hole becomes larger as the eye is heated.

What Causes Expansion?

Atoms in a solid are packed close together and they attract each other with such a strong force that they are held in place, forming a rigid pattern (or lattice, as it is sometimes called). When the solid is heated, the atoms absorb heat energy and they vibrate back and forth at a steadily increasing rate. As a result of their increasing kinetic energy, they push each other a little further apart and therefore occupy a little more space. In other words, expansion is caused by an increase in the space between atoms.

A Thermostat

If the metal screw cap of a jar becomes stuck, it can usually be loosened by dipping it in hot water. This is a good experiment to try, because it illustrates the important fact that different substances expand at different rates. In hot water the metal expands more than the glass; therefore, it no longer grips the glass tightly.

A very important application of the different rates of expansion is the bimetal strip. If two pieces of metal–steel and brass, for example–are riveted firmly together, they form a straight bar. But if the bar is heated or cooled, it will bend. Why is this? Brass expands more than steel, so that if the bar is heated, it will bend with the brass strip on the outside of the curve. Can you explain why?

Experiment

15-3. Expansion and contraction of a bimetal strip

Gently heat a bimetal strip of brass and steel in a Bunsen flame. Notice that the bar bends in such a direction that the brass is on the outside. Now plunge the strip into a jar of ice water and notice that the curvature is reversed; that is, steel is now on the outside of the curve. Why?

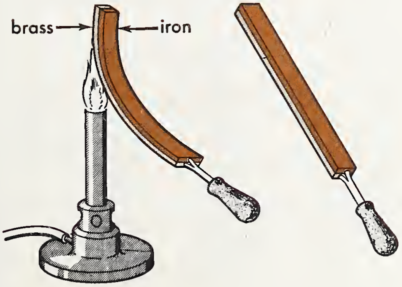


Fig. 15-7. Why is brass on the outside of the bend when this bimetal strip is heated?

The end of the bimetal strip moves through a curved path. The length of this path is far greater than would be the expansion of the metal strips along their own length if heated separately. This "magnifying" effect is used in a thermostat, a device for maintaining a constant temperature. You may be familiar with the thermostat in your house that controls the operation of an oil or gas furnace. The way it works is shown in Fig. 15-8. If the temperature in the house drops, the coiled bimetal strip bends outward, forcing the movable arm to the right so that it closes an electric circuit. A current then flows, a motor is started, and the oil is ignited. When the temperature rises above the point at which the thermostat is set, the bimetal strip bends inward, breaks the contact, and turns off the furnace.

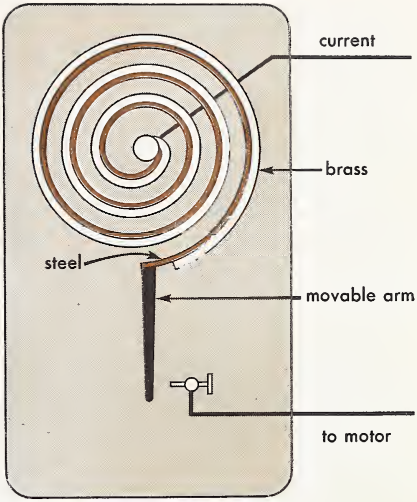


Fig. 15-8. A thermostat. As the temperature falls, the bimetal coil unwinds, closing an electric circuit which starts a motor and ignites the oil.

As we shall see in Chapter 17, a bimetal strip is also used in one type of thermometer.

Contraction on Cooling

The force of expansion makes it necessary to build a bridge in sections and to use expansion joints to prevent the bridge from buckling. Similarly, a force is exerted during contraction. This force was put to practical use by the early North American settlers in fastening iron tires to wagon wheels. First they made a tire a little smaller than the rim of the wheel. Then they heated the tire in a bonfire until it was large enough to slip over the rim, and, when the tire was in place, they poured

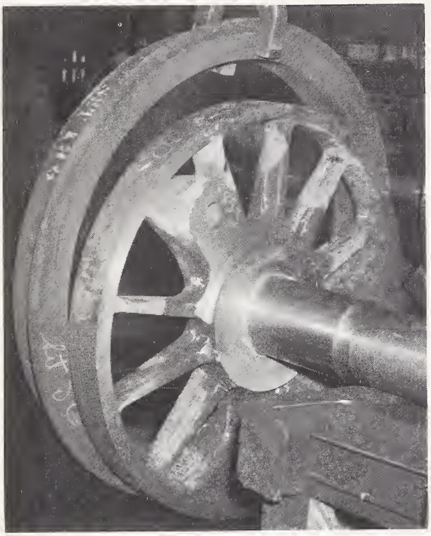


Fig 15-9. Fitting a hot metal tire to a locomotive wheel. As the tire cools, it shrinks and firmly grips the rim of the wheel.

cold water over it. As the iron tire contracted it gripped the wheel with such force that nails were unnecessary to keep it in place.

Today, steel tires are placed on locomotive wheels in precisely the same way. A locomotive wheel can, like an old shoe, be repaired. When the outer rim or tire wears thin it is removed from the wheel and a new one put in its place, and the force of contraction holds it in place. Next time you are near a locomotive, notice the steel tires on the big driving wheels.

Steel rivets are another example of a useful application of the force of contraction. Rivets may be used to tie steel beams together or to hold in place steel plates used in the construction of ships. The rivets, like the wagon rims, are first heated. Red-hot rivets are then forced through holes in overlapping plates and the ends are hammered and flattened. As the rivets cool they contract; the force of contraction holds the plates together making a strong, tight joint.

Expansion of Liquids

We are familiar with the expansion of mercury and alcohol because they are used in thermometers. As the mercury in a thermometer is heated, it expands through a narrow tube; the farther it goes up the tube, the higher is the temperature it registers. Expansion also occurs in a water heating system. Here the boiler is filled with water and so are the radiators and pipes. There must be room for the heated water to expand, otherwise even the steel joints in the pipes would crack and leak under the strain. An expansion tank, usually placed just under the roof, is provided for this purpose. The following experiment shows how liquids expand when heated.

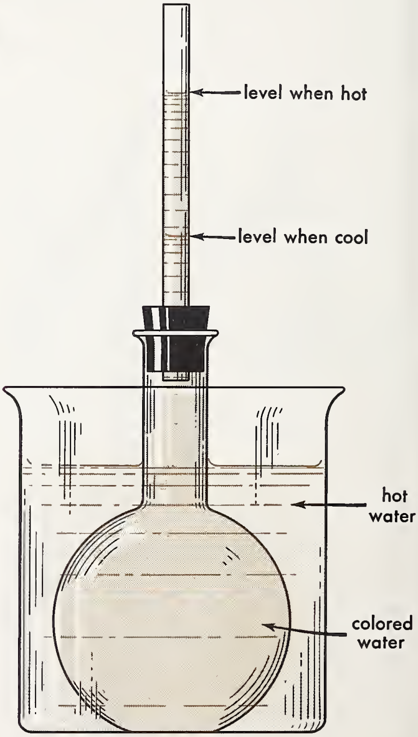


Fig. 15-10. Water expands when it is heated.

Experiment

15-4. The expansion of water

Add some red ink to water to make it clearly visible, and then fill a small flask with it. Insert a rubber stopper and glass tube in the neck of the flask as shown in Fig. 15-10. When the stopper is forced into the tube, water rises part way up the tube. Immerse the flask in a beaker of hot water. Carefully observe any movement in the water column at the instant the flask is immersed in the hot water.

You probably noticed that the top of the water column first dropped slightly and then rose rapidly. How can you explain this? The slight drop was caused by the expansion of the glass container, which became hot before the water inside; the steady rise is due to the expansion of the water. The experiment proves that water expands more than glass; if both expanded by the same amount, the water column would not rise in the tube. Allowance is made for expansion when ginger ale bottles are filled and capped. You may have noticed that the ginger ale never quite fills the bottle; a space is left to allow for the expansion that must take place if the ginger ale is warmed—as it would be if exposed to the sun. If the bottle were completely filled, it would leak or break when warmed.

Water, a Peculiar Liquid

You will learn later that water has several unusual properties. One of them is that it expands when it freezes. This is not the way nature usually behaves; liquids usually contract on freezing or solidifying. Consequently, solids are usually denser than liquids; solid mercury, for example, is denser than liquid mercury.

Since water expands on freezing, it follows that ice is not as dense as water and it therefore floats in water. The consequences of this unusual behavior are of great importance in nature. Let us see what happens when ice forms on top of a lake. The ice, which is a poor conductor of heat, acts like an insulating blanket and retards the cooling of the water below the ice. As a result, the lake does not usually freeze into a solid mass, and aquatic life is able to survive the winter. If ice were denser than water, it would sink to the bottom. More ice would then be formed and this, too, would sink. This process would continue throughout the winter until the lake was frozen solid, and both plant and animal life in the lake would be seriously harmed.

Expansion of Gases

The molecules of a gas are widely separated, so that there is little attraction between them. Therefore, they readily respond to even the slightest changes in temperature and expand much more than liquids or solids. The following experiment illustrates the expansion of a gas when heated.

Experiment

15-5. The expansion of air

Fit a stopper and tube into a 500-milliliter flask and support the flask so that the end of the tube is under water as shown in Fig. 15-11. Gently heat the flask with a Bunsen flame. Air bubbles at once escape through the water. Remove the burner. The air in the flask cools and contracts, and water rises up the tube. When the liquid has stopped rising, grasp the flask in your hands and notice that even the heat of the hand is enough to cause the air to expand so that water is forced down the tube.

The above device can be used as an air thermometer which, as you can see, is quite different from a mercury thermometer. An air thermometer was in fact the earliest kind of thermometer to be used; it was invented by Galileo in the seventeenth century. How could this device be used to measure the temperature of an object? First, the bulb would be placed in contact with the object. A drop in the water column

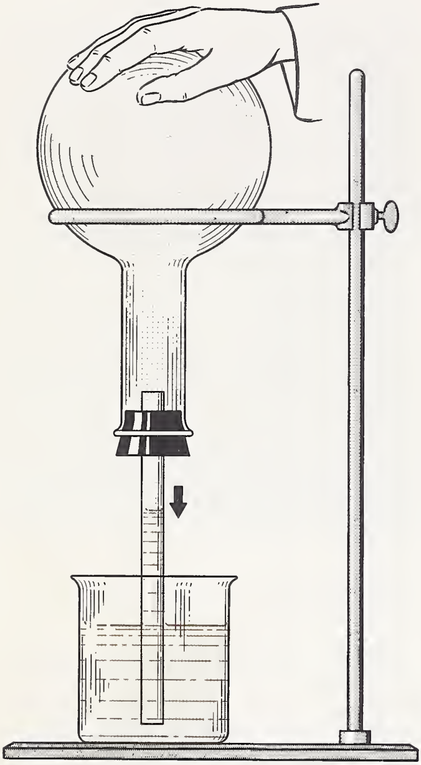


Fig. 15-11. A hand placed on the flask is enough to cause the air to expand noticeably.

would indicate that the temperature of the object is higher than the temperature of the air; a rise in the water column would indicate the reverse. To measure the temperature in degrees, however, it would be necessary to attach a scale to the glass tube. We shall discuss thermometer scales in Chapter 17.

Gas Pressure Changes with Temperature

We have already stated that there are relatively large spaces between the molecules of a gas. In other words, the actual volume of the molecules is only a *very* small fraction of the volume of the gas; the rest is empty space. For example, the actual volume of the molecules of air makes up only about one-thousandth of the whole volume of the space they occupy, so that 0.999 of the space is unoccupied by molecules.

Gas molecules move rapidly in all directions even at ordinary temperatures. If the temperature is raised, the speed of the molecules is increased and, if the gas is in an open flask, it expands and some of it escapes.

Experiment

15-6. The escape of air from a heated flask

Arrange a tightly fitting balloon over the outlet of a one-liter flask as shown in Fig. 15-12. Place the flask on an electric hot plate, and leave it there for 15 minutes or so. The balloon is slowly inflated by the expanding air as it leaves the flask.

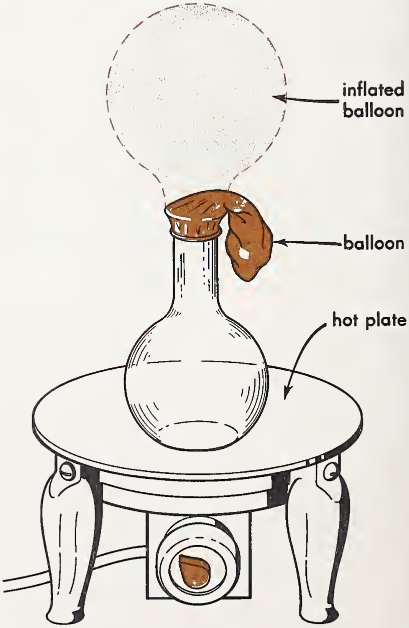


Fig 15-12. The balloon is inflated by heated air.

Suppose, however, that the gas is in a closed container so that it cannot expand. What, then, would be the effect of heating the gas? The molecules strike the walls of the container and rebound; the more the gas is heated, the faster is the motion of the molecules and the more frequent are the impacts with the walls. It is therefore apparent that ***if an enclosed gas is heated, its pressure increases; and conversely if the gas is cooled, its pressure decreases.***

Experiment

15-7. To reduce the pressure of a gas by lowering its temperature

Heat a gallon can with a Bunsen flame and, while it is still hot, screw on the metal cap. Now hold the can in a stream of cold water and observe that the walls begin to bend inward.

What caused the can to buckle? When the can was heated, some of the air molecules escaped so that, when the cap was screwed on, the can had fewer molecules than normal. Moreover, the cold water slowed down these remaining molecules. Hence the molecular bombardment of the container on the inside was diminished on both counts and, in consequence, the inside air pressure was reduced. However, the container is also bombarded by atmospheric air molecules outside, and this bombardment has not been diminished. The result it that the outside pressure exerted *inward* exceeds the inside pressure exerted *outward* and the sides of the can bend inward.

A Gas is Heated by Compression and Cooled by Expansion

When air is pumped into a bicycle tire, the pump becomes quite warm. Why is this? Where does the heat come from? As the piston is forced into the pump, it strikes air molecules which then rebound from the piston with increased speed, just as a baseball does after it has been struck by a bat. After several strokes of the piston, the molecules are speeded up considerably, which means that the gas has become hotter. We shall read in Chapter 25 that the operation of a diesel engine depends on the heat generated by the compression of air. Air in the cylinder of a diesel engine is highly compressed and becomes so hot that fuel oil burns instantly when injected into the hot air.

Let us now examine the reverse effect. Does a gas become cool as it expands? If you place your hand in the rapid stream of air escaping through the valve of an automobile tire, you will notice that the air feels cool. How can we explain this? As the crowded gas molecules escape through the valve they frequently collide with air molecules outside. In this way they are slowed down and, as a result, they lose energy and become cooler. A familiar example of cooling by expansion is the dry carbon dioxide fire extinguisher. As the carbon dioxide escapes under pressure from the tank, it becomes so cold that a cloud of dry ice is formed. Cooling by expansion is also fundamental to the operation of a steam engine, discussed on page 234.

Things to Remember

Solids expand when heated and contract when cooled.

Different solids and liquids have ***different rates of expansion***; but all gases have the same rate of expansion.

Gases expand more than solids or liquids when heated through the same range of temperature.

Liquids contract on freezing; water is an important exception to this rule.

The *pressure of a confined gas* increases if the gas is heated; conversely, the pressure decreases if the gas is cooled.

When a gas is compressed, ***its temperature rises***; when a gas expands, ***its temperature falls***.

Questions

Part A

1. A telephone wire sags more in summer than in winter. Why?
2. Laboratory beakers are usually made of pyrex glass, rather than ordinary glass. Why?
3. What is a thermostat?
4. Why are *hot* rivets used to hold steel plates in position? Explain.
5. "Water does not behave like most other liquids as it freezes." Explain what this statement means.
6. State two differences between the expansion of solids and gases.
7. Air which escapes through the valve of an automobile tire feels colder than the surrounding air. Why?

Part B

8. Describe an experiment to show that steel and copper have different rates of expansion.
9. Will the hole enclosed by a metal ring get larger or smaller as the ring is heated? Explain.
10. Explain how the bimetal strip of a thermostat operates.
11. Explain why a solid expands when it is heated.
12. How is the survival of fish life in a lake related to the fact that water expands as it freezes?
13. Draw a diagram of an air thermometer and explain how it operates.
14. Explain why the pressure of a gas increases if the gas is heated.
15. A gas in a cylinder is suddenly compressed by a piston. The compressed gas is then released through a small opening in the top of the cylinder. Does the gas undergo any temperature changes? Give reasons for your opinions.

Things to Do

Water expands on freezing

Completely fill an 8-ounce screw-cap bottle with cold water and tightly screw the top on the bottle. Now place the bottle in a pail and pack a freezing mixture of ice and salt around it. (The ice should be finely ground.) Use a dipper to pack the ice and salt around the bottle—the proportion should be 3 dippers of ice to 1 of salt. Continue until the bottle is completely covered by the freezing mixture. Then put the pail aside and the bottle will probably burst in 15 or 20 minutes.

16

Transmission of Heat

A good way to study the transfer of heat is to examine a hot-water heating system. How does heat from the oil or gas burner in a basement warm up the rooms of a house? First, heat from the flames is conducted through copper coils in the firebox of a furnace. Water in the coils is heated and flows through pipes and radiators, and then back to the furnace. Heat from the hot water in the radiators is conducted through the metal and into the room. Notice that heat is transmitted through three different substances—water, a metal, and air; and the methods of transmitting heat through these substances are quite different. Heat can be transmitted in three different ways—by ***conduction, convection,*** and ***radiation***; each of these plays a part in a house heating system.

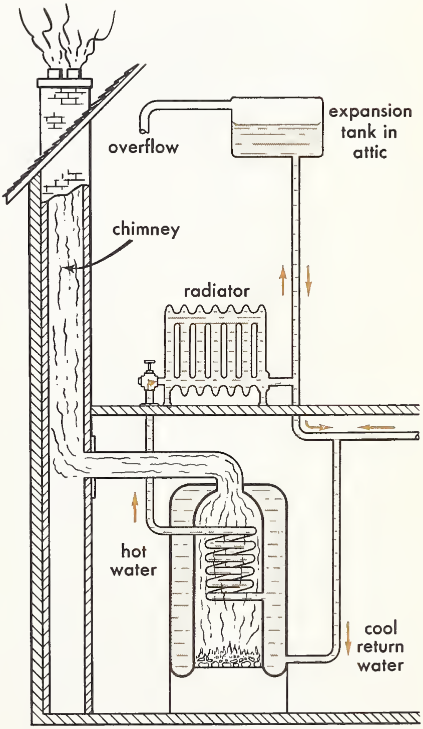


Fig. 16-1. A hot-water heating system. Heat from the flames is transferred to the air in the room mainly by convection currents in hot water.

Conduction

We know that if one end of a copper wire is held in a Bunsen flame, heat travels along the wire so that the whole wire soon becomes uncomfortably hot. How is heat transmitted in the solid wire? Copper atoms absorb heat energy from the flame and their rate of vibration increases. The fast vibrating atoms collide with some slower vibrating atoms a little further from the flame thereby transmitting some of their kinetic energy to the slower atoms. These atoms, in turn, collide with other nearby atoms so that, eventually, the rate of vibration of the atoms is speeded up all along the wire. This method of transmitting heat is called *conduction*. Thus we can say that ***in conduction heat is transmitted from atom to atom by impact.***

The conductivity of different solids varies a good deal. All metals are good conductors; aluminum pots and pans, for instance, make excellent cooking utensils because of their good conductivity. Most nonmetals, however, are poor conductors.

Silver is the best conductor, and copper the next best. The conductivity of copper gauze can be shown in the following experiment.

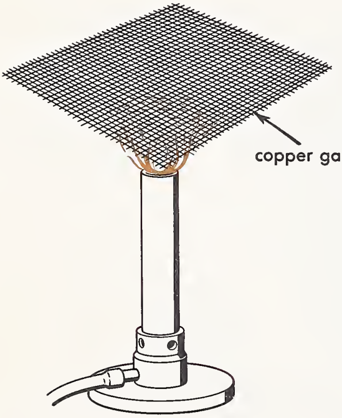


Fig. 16-2. Copper gauze stops the flame of a Bunsen burner because it is a good conductor of heat.

Experiment

16-1. The conductivity of copper gauze

Lower a piece of copper gauze onto a Bunsen flame. The flame does not pass through the gauze. Instead, as the gauze is lowered, the flame appears to be pushed down.

Why does the flame not pass through the gauze? The reason is that the heat of the flame is conducted along the strands of copper and, as a result, the gas is cooled so much that it cannot burn above the gauze. That is to say, the copper gauze cools the fuel gas below its ignition temperature. This effect was discovered by Humphry Davy and is referred to in Chapter 1. You will recall that Davy made a safety lamp for coal miners by placing a frame of copper gauze around the flame of an oil lamp (see Fig. 1-4). He realized that inflammable mine gases would pass through the gauze and be ignited inside the gauze by the flame of the lamp. However, the hot gases formed in the flame were cooled so much as they passed through the gauze that they were below the kindling temperature of the mine gases outside. Therefore the inflammable mine gases were not ignited and an explosion was prevented.

Poor Conductors of Heat

Nonmetals such as wood, cloth, and glass are poor conductors; their atoms do not transmit motion easily. A glass tube, for instance, can be safely held in the fingers while part of it is strongly heated. Wooden or plastic handles are usually attached to electric irons, soldering irons, and coffee pots. Rocks are also poor conductors. Exposed surfaces of rocks are heated by the sun and expanded. Since the underlying rock layers do not receive much heat, they do not expand and, consequently, strains are set up which crack the rock surface. This, you may recall, is one of the causes of weathering, or disintegration of exposed rock surfaces.

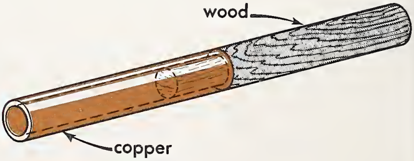


Fig. 16-3. This composite rod can be used to show that copper is a better conductor of heat than wood. How?

Experiment

16-2. To compare the conductivity of wood and copper

Use a composite rod, part wood and part copper, as shown in Fig. 16-3, for this experiment. Wrap a single layer of white paper around the middle of the rod and hold the paper tightly in place. Move the rod and paper back and forth in a Bunsen flame, heating it near the joint between the wood and the copper. Notice that the paper over the wood becomes scorched, whereas the paper over the metal does not. How can you explain this?

Wood, being a poor conductor, is unable to transmit heat from the flame along the wood. Therefore, the wood becomes very hot on its surface and the paper over the wood is scorched. Since copper is a good conductor, its surface is much cooler than the wood, and the paper covering the copper is not scorched.

All liquids, except molten metals, are poor conductors. Water, for instance, is a poor conductor as is shown in the following experiment.

Experiment

16-3. To show that water is a poor conductor

Place a piece of ice in a 1-inch test tube and put a small lead weight on the ice to prevent it from floating. Fill the test tube with ice cold water, slope the tube, and heat the water near the top as is shown in Fig. 16-4. The surface water soon boils, but the ice remains unmelted. Very little heat is conducted through the water, otherwise the ice would have melted.

Gases are Poor Conductors

The molecules of gases are too far apart to transfer heat energy easily by collision. ***All gases are, therefore, poor conductors of heat.***

The poor conductivity of air has numerous applications. Blankets and woolen clothing, for example, have many air spaces between their fibers. The "dead" air in the spaces prevents loss of heat from the body and so keeps us warm. Asbestos, cork, sawdust, and "rock wool" have insulating properties because of the "dead" air meshed in the spaces. Insulating rock wool or asbestos is therefore put between the walls of an oven to keep heat in, and between refrigerator walls to keep heat out.

Insulation is also a factor in air conditioning; the same insulation keeps a house warm in winter and cool in summer. To keep a house warm the heat supplied by the furnace must not be allowed to escape outside. To prevent this, rock wool–a fluffy material made by blowing compressed air through molten slag–is forced between the inner and outer walls of a house and also under the roof. Insulation saves fuel; the cost of installing the insulation is soon offset by the reduced cost of the fuel.

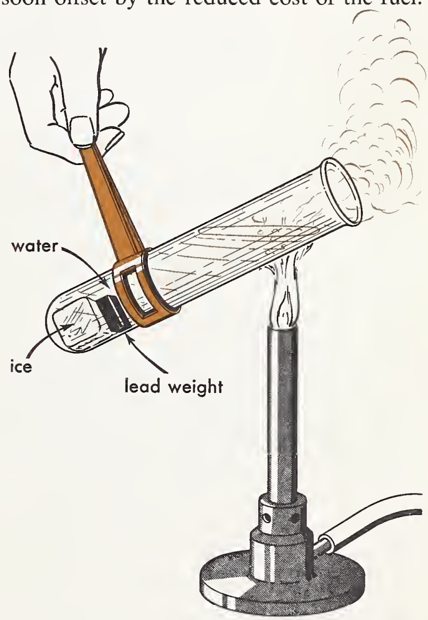


Fig. 16-4. Water does not conduct enough heat from the boiling water to melt the ice.

Fig. 16-5. Placing insulating material along the outer walls of a building keeps it warmer in winter and cooler in summer.

Convection

Your hand feels much hotter if it is held above a light bulb than if it is held below it. Why is this? It is because the air around the bulb is heated by contact with the hot glass; as a result, it expands, becomes less dense than the surrounding air, and rises, carrying heat with it. This flow of air is called a *convection current*. Since convection implies a flow of heated material it cannot apply to solids, but only to fluids; that is, to liquids and gases.

A convection current in air is shown in the following experiment.

Experiment

16-4. Convection in air

A box with a glass front is fitted with two glass chimneys, as shown in Fig. 16-6. Place a burning candle under one of the chimneys and hold a smoking paper (touch paper) above the other. Notice that the smoke is carried in the air stream of the convection current.

Hot air above the candle rises up the chimney. Cool air comes down the other chimney to replace it. This cool air, in turn, is heated by the candle, and rises and escapes by the updraft chimney. The convection current carries away the heat of the candle flame and, as it does so, cool air is constantly drawn in. This apparatus shows how coal mines were ventilated in the eighteenth century. The mine had two shafts, and a coal fire was burned at the bottom of one of them. The upward convection current caused a downdraft of fresh air through the other shaft, thus providing the miners with essential ventilation. This method of ventilating mines was dangerous; not infrequently, the explosive mine gases were ignited by the fire. Today coal mines are ventilated by powerful electric fans.

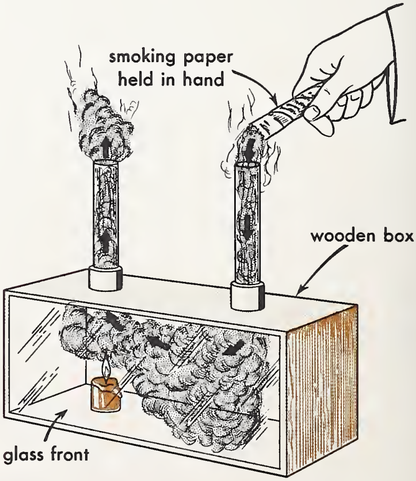


Fig. 16-6. A smoke box shows convection currents in air.

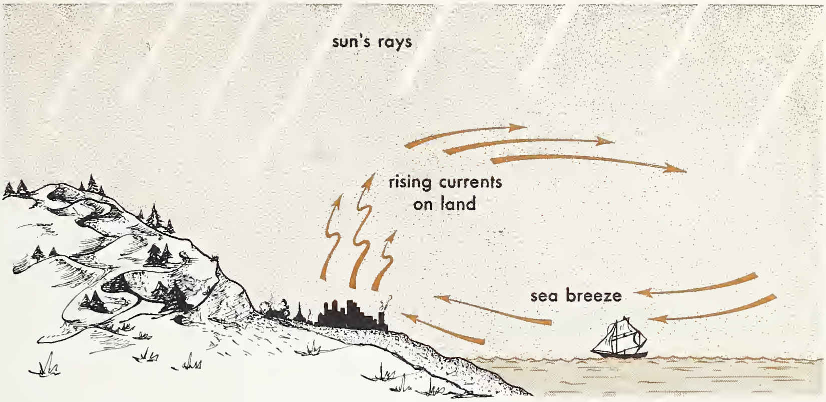


Fig. 16-7. A sea breeze is caused because the sun heats the earth more than the sea.

Winds

The heat received by the earth from the sun depends on a number of factors, so that varying amounts of heat are received in different places. As a result huge convection currents in the atmosphere are set up. The motions of these currents of air across the earth's surface are called *winds*. Trade winds and land and sea breezes are typical large-scale convection currents.

Land and Sea Breezes

Land and sea breezes blow near the shore of the sea or a large lake. Let us first consider a sea breeze which begins as a gentle wind during the forenoon of a sunny day, blows strongest in the early afternoon, and dies out completely in the evening. How is a sea breeze formed? Both land and water absorb the heat of the sun. However, as we shall learn in Chapter 18, land heats up faster than water, so that air over the land is warmer than air over the water. The warmer land air expands and rises; cooler air flows in from the water to replace it. This air current moving from water to land is a ***sea breeze***.

A sea breeze is a cool refreshing wind that does not extend very far inland. When approaching the coast on a hot summer day you suddenly become aware of this refreshing breeze blowing in from the sea.

A ***land breeze*** blows at night from land to water. How is a land breeze formed? Bearing in mind that, during the night, land cools more rapidly than water, you ought to be able to answer this question.

Convection in Water

Water, like air, is a good convector of heat as can be shown in the following experiment.

Experiment

16-5. Convection in Water

Nearly fill a 1-liter beaker with water and support it as shown in Fig. 16-8. Drop a few crystals of potassium permanganate into the beaker. (These crystals dissolve to form a purple solution which will indicate the path of a convection current.) Heat the bottom of the beaker near one side. A convection current, which follows the arrows in the diagram, is soon observable.

What causes the current? The heated water at the bottom of the beaker expands and rises; colder, denser water then falls,

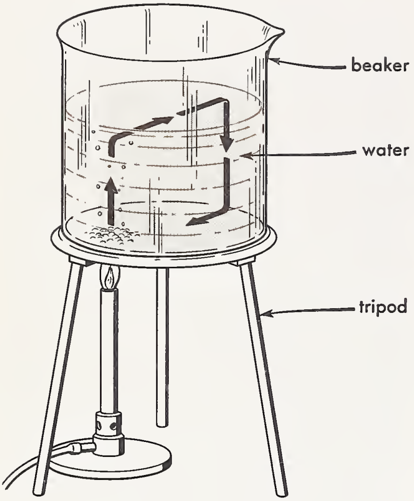


Fig. 16-8. A convection current in heated water.

taking the place of this warmer, lighter water. During the rise and fall of the convection current, hot and cold water mix so that the water in the beaker becomes warmer. The transfer of heat in a hot-water heating system depends, of course, on the convection currents set up in water.

Experiment

16-6. A hot-water heating system

Set up the apparatus as shown in Fig. 16-9. Notice that the bent outlet tube extends from the top of the flask to the top of the expansion bottle; the straight inlet tube extends from the bottom of the expansion bottle to the bottom of the flask. Pour water into the apparatus until the outlet of the upper tube in the expansion tank is covered. Now pour in a little red ink to make the flow visible, and then heat the bottom of the flask. In a few minutes the water circulates freely in the direction shown by the arrows. Why does the water *rise* in the side loop? Why does it *fall* in the straight tube?

Radiation

So far we have considered conduction, a transfer of heat caused by the impact of atoms, and convection, caused by a flow of large numbers of molecules. But neither conduction nor convection can account for the passage of heat from the hot filament to the glass wall of the tube in a radio set. The radio tube is evacuated; it contains almost no air and, therefore, there are very few molecules to transmit the heat. Then how does heat reach the glass walls of the bulb? It is evident that this heat energy can be transmitted through a vacuum. ***The process by which energy is transferred through space is called radiation.***

Heat from the sun comes to us by radiation. The sun radiates heat in all direc-

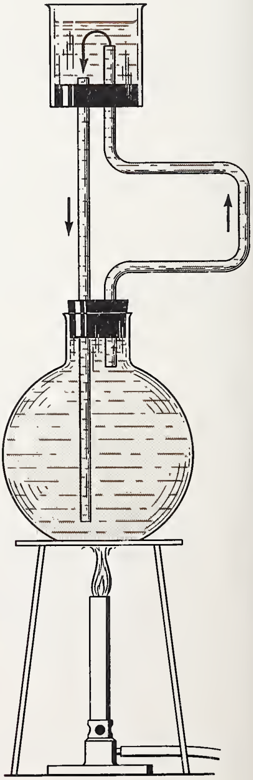


Fig. 16-9. A miniature hot-water heating system showing convection currents.

tions, but since the earth is about 93 million miles away, only a tiny fraction of the sun's radiation reaches us. Yet all plant and animal life depends on it; if the sun ceased to radiate energy the earth would soon be a lifeless place.

Radiant energy comes to us as waves which travel through space with the speed of light–186,000 miles per second. If these waves are absorbed, as they are when they strike the earth, their energy is converted into heat, and the earth is warmed by them.

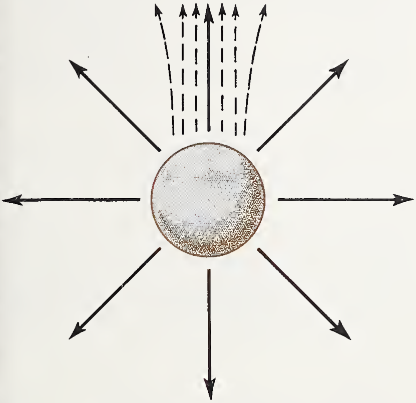


Fig. 16-10. Heat losses from a hot ball. The dotted lines represent convection losses; the black lines represent radiation losses.

Let us, for a moment, consider how a hot metal ball, supported by a wire, can lose heat to its surroundings. The loss of heat by conduction would be slight. Why? The loss by convection would be considerable and in an upward direction. Why? The loss by radiation would also be considerable, but in all directions. These heat losses are illustrated in Fig. 16-10. The diagram shows clearly why the hand placed below the ball will feel hot, and why the hand placed the same distance above the ball will feel hotter. The diagram also shows why a coal or wood fire heats a room mostly by radiation; most of the heat carried off by convection goes up the chimney.

Absorption of Heat

As stated above, substances interfere with the passage of radiant energy; some substances absorb it and thereby become warmed, other substances reflect it and are therefore not perceptibly warmed by it. Radiant heat energy, like light (which is also a form of radiant energy), is absorbed by dark surfaces and reflected by white or shiny surfaces. You may have noticed that a dark-colored object such as a leaf slowly sinks through snow when the sun shines so that, after a few days, it may be several inches below the surface. This is because the dark leaf absorbs the sun's radiation and becomes warm enough to melt the snow underneath. For the same reason, a dark winter suit is warmer than a suit of light-colored cloth of the same material. On the other hand, people in the tropics usually wear white clothing. Can you explain why?

There is one final point concerning radiation that should be mentioned. It can be shown that ***good absorbers of radiant energy are also good emitters or radiators of it.*** On the other hand, poor absorbers are poor emitters. These facts are significant when we consider the surface that will best emit heat from a steam radiator. It is apparent that the best emitter is one with a dull black surface. A dull black radiator in a modernistic drawing room may not harmonize with the color scheme, but it is the most efficient emitter of heat.

A Radiometer

A radiometer, as shown in Fig. 16-11, is a device which shows the presence of radiant energy. It consists of four vanes mounted on a shaft, the whole being enclosed in a glass bulb from which most of the air has been removed. Each vane has a shiny face, and a dull black face. The shiny face reflects radiation; the dull face absorbs radiation and, as a result, becomes hot. Air

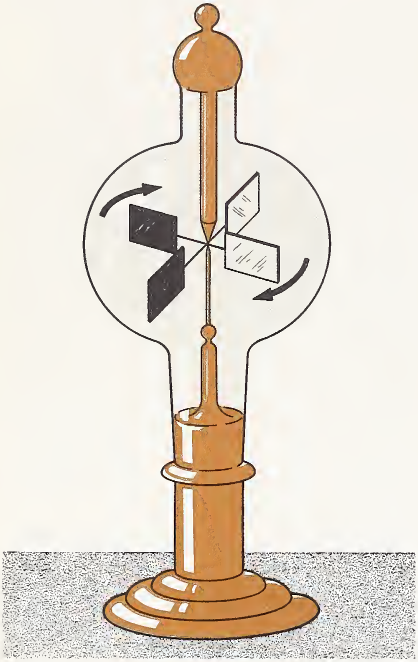


Fig. 16-11. The vanes of a radiometer whirl rapidly when heat falls upon them. Why?

molecules near the shiny face are unaffected, but those near the dull face are heated. The heated molecules move about rapidly, push against the black surface, and so cause the vane to rotate. In other words, radiation causes the rotation of the vanes.

Experiment

16-7. A radiometer responds to radiation from a hot coil

Pass a current through a heating coil. Now gradually move a radiometer toward the red-hot coil. The speed of rotation of the vanes gradually increases as the coil is approached.

Heating Systems

Originally, houses were heated by burning coal or wood in a fireplace. The room was heated chiefly by radiation, but most of the heat was carried away as a convection current up the chimney. Stoves were not used until the eighteenth century. The great advantage of a stove is that it heats a room by convection as well as by radiation. In modern houses stoves have been replaced by a central heating system that uses air, water, or steam. All three systems have a firebox in the furnace to provide heat, which is then distributed to all parts of the house.

A Hot-Air System

In a hot-air system, the firebox is surrounded by a metal jacket from which large pipes lead to the various rooms of the house. Hot air is forced through the pipes by a fan. It enters a room through a duct, circulates through the room by convection, thereby losing heat and, finally, as cool air, it flows through a return pipe to the furnace where it is reheated and recirculated. The arrangement is shown in Fig. 16-12.

A hot-air system is the least expensive of all to install and is satisfactory for small houses. Perhaps its most objectionable feature is the noise of the fan.

A Hot-Water System

In this system, a tank extends around the sides and top of the firebox. Steel or copper coils near the top of the furnace make up the heating unit. Water circulating through these coils is heated by burning fuel. The hot water rises through a pipe to a radiator, where heat is distributed to the rooms by convection and radiation. A pipe from the radiator returns the water to the furnace for reheating.

A hot-water system is shown in Fig. 16-1. Notice that the furnace pipes and radiators are completely filled with water. Some

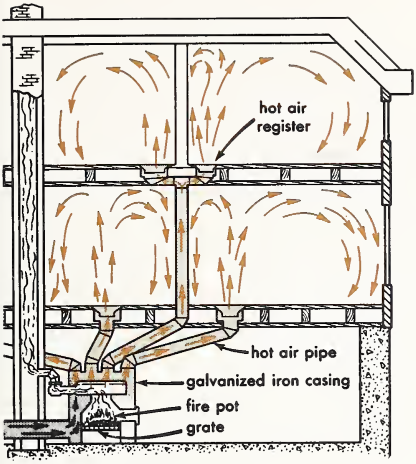


Fig. 16-12. A hot-air heating system.

provision must therefore be made for its expansion, and, as stated on page 146, a tank is supplied for this purpose.

A Steam System

This is similar in design to a hot-water system. There is, however, an important difference. As we shall read in Chapter 19, it is the condensation of steam to hot water that supplies most of the heat in this system. The condensed steam, as hot water, flows back to the boiler by a separate pipe.

Both water and steam systems provide more uniform heating than the air system, but they are more expensive to install. Much more piping is needed, drainage systems are necessary and, in addition, steam pipes should be insulated against heat losses.

A Thermos Flask

A thermos flask is a simple device which is designed to prevent heat losses by conduction, convection, and radiation. It serves a double purpose: it keeps hot liquids hot, or cold liquids cold.

The thermos flask has a double wall. The walls of the flask are silvered and air is removed from the space between them. If the flask is closed by a cork stopper, hot water in the flask will remain hot for several hours. How does a thermos flask manage to prevent heat losses? Heat from the hot liquid cannot escape to the outside by convection because of the vacuum; there are no air molecules to convey heat across the space. Nor can heat escape by radiation. The silvery surface is a good reflector of heat so that radiation is reflected back and forth inside the flask. The only heat loss is by conduction through the glass at the top and the cork stopper, and this loss is very small.

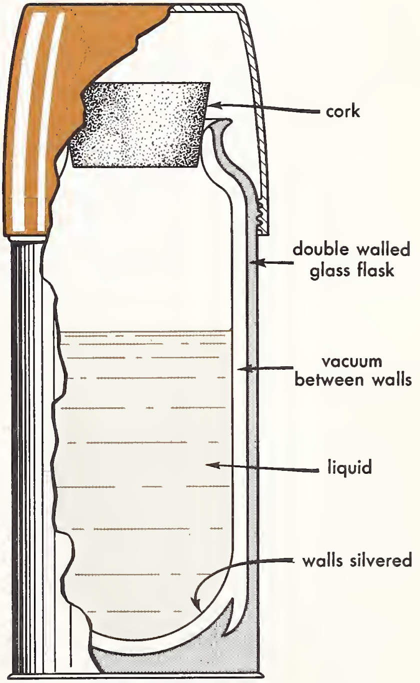


Fig. 16-13. A thermos flask prevents heat losses by convection and radiation.

Things to Remember

Heat can be transmitted in three ways: by ***conduction, convection,*** and ***radiation.***

Conduction is the transfer of heat by impact between the atoms or molecules of a substance.

Metals are good conductors of heat; most ***nonmetals*** and ***liquids,*** and all ***gases*** are poor conductors.

Convection is the transfer of heat by fluid currents.

Radiation is the transfer of heat through space by waves similar to light waves.

Good ***absorbers of radiation*** are also good emitters of it.

White or shiny surfaces ***reflect*** heat; dark surfaces ***absorb*** it.

Questions

Part A

1. State whether the following are good or poor conductors, and good or poor convectors: [**a**] air, [**b**] mercury, [**c**] water, [**d**] copper.
2. A silver spoon soon becomes too hot to touch if placed in a cup of boiling water. How is heat carried from the water to the handle?
3. A beaker of water is heated in a Bunsen flame. How is heat carried from the bottom to the top of the water?
4. Why do convection currents not occur in solids?
5. If one hand is placed above a hot ball and the other below it, the hands are heated unequally. Why?
6. How do the atoms of a solid transfer heat by conduction?

Part B

7. What is rock wool and why is it used to insulate houses?
8. How would you prove by experiment that water is a poor conductor of heat?
9. Describe and explain what happens if a copper gauze is lowered over a Bunsen flame.
10. On a winter day linoleum may feel cold, whereas a rug in the same room and at the same temperature may feel warm. Why?
11. Explain, with a diagram, how a sea breeze may be formed.
12. In designing a hot-air system, would you plan to have the warm air enter a room near the floor or near the ceiling? Explain.
13. Describe the steps in the transfer of heat in a hot-water furnace system, from the fire to objects in a room.
14. An air-cooled airplane motor has many fins on the outside of the cylinders. Why?
15. Explain the significance of the statement that good absorbers of radiation are also good emitters of it.
16. Explain how a radiometer works.
17. Explain how a thermos flask prevents heat losses by conduction, convection, and radiation.

Things to Do

Convection in Water

Select two bottles of the same size (pop bottles are satisfactory).

Into one pour two tablespoonsful of ink (red or black). Fill this bottle with hot water. Fill the other bottle with very cold water. Cover the cold bottle with a piece of heavy paper (2 in. × 2 in.), then press on the paper so as to squeeze a little water out of the bottle. Now make sure that the hot bottle is completely filled. Invert the cold bottle over the hot one so that their mouths coincide exactly. Carefully remove the paper. A stream of colored water then rises into the upper bottle. Why?

17

Temperature

According to the kinetic theory, gas molecules are in a state of rapid motion; the hotter the gas, the more rapid is the motion of its molecules. Because of their motion, molecules have kinetic energy. Therefore, we can say, the hotter the gas, the greater is its kinetic energy. ***Temperature is a measure of the kinetic energy of gas molecules.***

How can we measure temperature? Or, rather, how can we measure the kinetic energy of molecules? It is impossible to measure the kinetic energy of molecules directly, but several indirect methods have been devised to do this. We know, for example, that the expansion of a body depends upon its rise in temperature. Hence, we can use expansion effects as an indirect way of measuring temperature. It should not, therefore, be surprising that there are such things as air thermometers, liquid thermometers, and metal (or rather, bimetal) thermometers.

The Sense of Touch as an Indication of Temperature

Before discussing some of these thermometers, however, we should bear in mind that the terms *hot* and *cold* were used long before anything was known about motions of molecules. The first concepts of hotness and coldness were derived through the senses, chiefly the sense of touch. But the sense of touch is very unreliable as a temperature indicator. For example, a temperature of 60°F seems warm in winter, whereas the same temperature feels decidedly cool in summer. The same misleading temperature sense can be experienced in the following experiment.

Experiment

17-1. The unreliability of touch in measuring temperature

Pour water into each of three beakers—hot water into one, ice-cold water in another, and tepid water in the third. Immerse the index finger of your left hand in the hot water and the index finger of your right hand in the cold water. After a minute or so, transfer both fingers to the tepid water. The sensation is quite different in each case; the finger of the left hand feels cold, that of the right hand feels warm.

An Air Thermometer

The first thermometer ever devised was invented by the Italian scientist Galileo around the year 1590. Some reference has already been made to Galileo's thermometer on page 147. It consisted of a glass bulb and stem. If the open end of the stem is held under water, and if the bulb is first warmed to expel some air and then cooled,

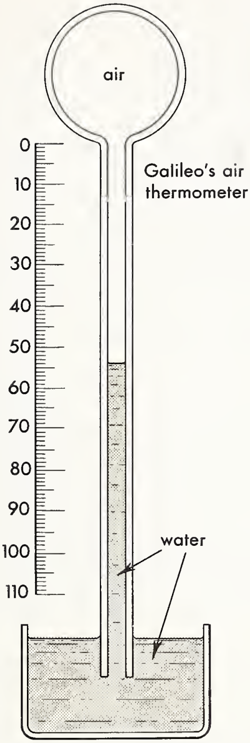


Fig. 17-1. Galileo's air thermometer. If the bulb is placed in contact with a hot object, the water column is forced down.

the water rises into the stem as shown in Fig. 17-1. This was Galileo's thermometer. How does it work?

If the bulb is placed in contact with a hot object, the motions of the air molecules in the bulb are speeded up. The faster-moving molecules exert a greater pressure so that the water column in the stem is forced down. The distance the water column falls is a measure of the temperature of a hot object.

Liquid thermometers are more convenient than air thermometers for ordinary purposes. But, as you will learn later, gas thermometers are still used by scientists when very accurate temperature measurements are needed.

A Fahrenheit Thermometer

The first liquid thermometer was invented by Daniel Fahrenheit, a German scientist, in 1706. Fahrenheit first blew a bulb at the end of a glass tube with a very narrow bore, called a capillary tube. He then filled the bulb and part of the tube with mercury, pumped air out of the tube and, finally, sealed the end of the tube by heating it. If this device is immersed in hot water, the mercury expands and rises up the capillary tube; conversely, if it is immersed in cold water, the mercury contracts and falls. But this is not a thermometer; a scale is needed before the device can register temperatures. And before a scale can be devised it is first necessary to select two convenient "fixed" points.

Fahrenheit selected the temperature of a mixture of ice and salt as the lower fixed

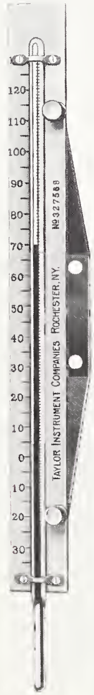


Fig. 17-2. A mercury Fahrenheit thermometer.

point; this he called zero degrees (0°). He took body temperature as the upper fixed point; this he called 24 degrees (24°). The divisions on this scale proved to be too large for practical purposes, and he later divided them into four parts. Thus body temperature on the new scale became 96° and this is the approximate value it has today. Actually, we know that body temperature is now more accurately recorded as 98.6°F and that, on this scale, water boils at 212°F and freezes at 32°F. Ordinary room temperature is about 70°F. The temperature on a cold winter day in Alberta may be –30°F, that is, 30 degrees below zero.

The Centigrade or Celsius Scale

A few years after Fahrenheit's invention, in 1742, a Swedish astronomer named Anders Celsius suggested a more convenient thermometer scale. He used the freezing point and boiling point of water as the two fixed points; the lower he called zero degrees (0°) and the upper he called 100 degrees (100°). On this scale there are 100 divisions or degrees between the lower and upper fixed points. This temperature scale is called the ***Celsius*** scale or, more often, the ***centigrade*** scale. For this reason, the letter C is used to indicate a Celsius or centigrade temperature. For example, water boils at 100°C, aluminum melts at 660°C, body temperature is 37°C, and the temperature corresponding to 0°F is about –18°C.

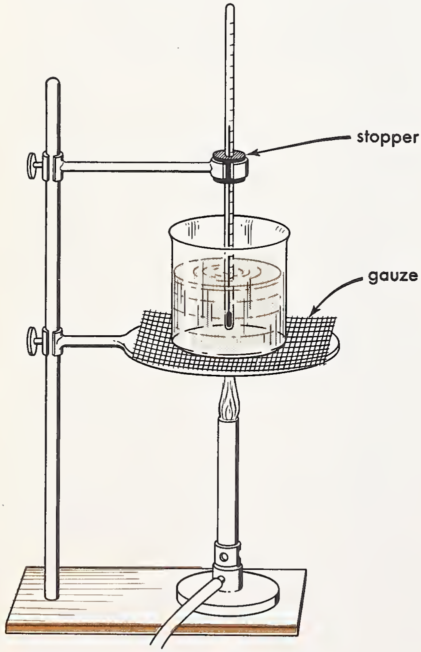


Fig. 17-3. Checking the upper fixed point of a thermometer.

In most countries the Celsius or centigrade scale is the only one used. However, in Canada, Great Britain, and the United States, both scales are used. The centigrade scale is used almost exclusively in scientific work, but the Fahrenheit scale is used for general purposes. For instance, weather and household temperatures are expressed on the Fahrenheit scale. A comparison of the two scales is shown in Fig. 17-4.

Experiment

17-2. To check the fixed points on centigrade and Fahrenheit thermometers

Lower Fixed Point

Use for this purpose a thermometer with two scales, centigrade and Fahrenheit. Put some cracked ice in a beaker and completely immerse the bulb of the thermometer in it. Observe that the mercury column falls and, eventually, it comes to rest with the top of the column opposite the mark which indicates 0°C and 32°F.

Upper Fixed Point

Support another two-scale thermometer in a beaker of water as shown in Fig. 17-3. Heat the water and observe the rise of the mercury column. Notice that, when the water boils, the top of the column remains steady. Read the temperature of boiling water on each scale. Are these readings what you expect?

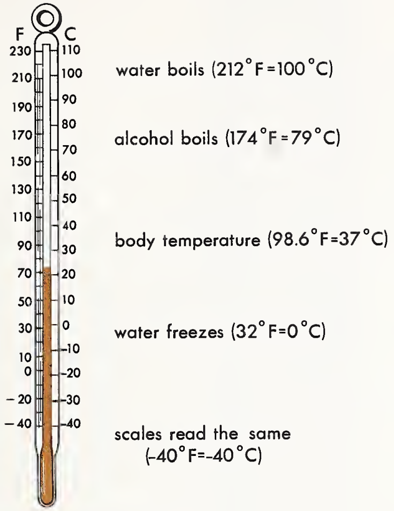

F
C
230
210
190
170
150
130
110
90
70
50
30
10
0
– 20
– 40
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
water boils (212°F=100°C)
alcohol boils (174°F=79°C)
body temperature (98.6°F=37°C)
water freezes (32°F=0°C)
scales read the same (-40°F=-40°C)

Fig. 17-4. A comparison of Fahrenheit and centigrade temperature scales.

To Compare Fahrenheit and Centigrade Temperatures

On the Fahrenheit scale there are 180 degrees between the boiling and freezing points of water (212–32 = 180); on the centigrade scale there are 100 degrees between the same two fixed points. Therefore, one degree on the centigrade scale is larger than one degree on the Fahrenheit scale. How much larger?

The ratio between the number of degrees on each of the two scales is 100 to 180, or 5 to 9. That is, one centigrade degree is 9/5 of a Fahrenheit degree in size, and one Fahrenheit degree is 5/9 of a centigrade degree in size. With this in mind we can readily convert a change in temperature on one scale to the corresponding change on the other. We simply remember that centigrade change = 5/9 Fahrenheit change, or Fahrenheit change = 9/5 centigrade change.

This relation can be used to solve problems like the following.

Example 1. Find the change in temperature on the Fahrenheit scale which corresponds to a change of 55 degrees on the centigrade scale.

Fahrenheit change
= 9/5 centigrade change
= $9/5 \times 55°$ = 99 Fahrenheit degrees

Example 2. Water in a beaker is heated from 35°F to 185°F. Find the change in temperature on the centigrade scale.

Centigrade change
= 5/9 Fahrenheit change
= $5/9\ (185° - 35°)$
= $5/9 \times 150°$ = 83.3 centigrade degrees

Another kind of problem involves the conversion of a temperature *reading* from one scale to another. Here we must bear in mind that a centigrade reading of 0°C corresponds to a Fahrenheit reading of 32°F. In converting a Fahrenheit temperature to the corresponding centigrade temperature, the first thing to do is to subtract 32, and then make the change to the centigrade scale by multiplying by 5/9.

Example 3. Find the centigrade temperature equivalent to 77°F.

1. Subtract 32.
   77–32 = 45
2. Multiply by 5/9
   $5/9 \times 45$ = 25°C

To change a centigrade temperature to a Fahrenheit temperature we must, of course, reverse the above process; that is, first multiply the centigrade temperature by 9/5 and then add 32 to the result.

Example 4. What Fahrenheit temperature corresponds to 45°C?

1. $45 \times 9/5 = 81$
2. 81 + 32 = 113°F

The above procedures can be summarized in the following rules:

1. *To change a Fahrenheit temperature to centigrade, subtract 32 and multiply by 5/9.*
2. *To change a centigrade temperature to Fahrenheit, multiply by 9/5 and add 32.*

Another way to change from a centigrade to a Fahrenheit temperature or vice versa is to make the necessary substitution in the formula $F = 9/5C + 32$.

Example 5. Find the centigrade temperature corresponding to 22°F.

$$F = 9/5C + 32$$
$$\therefore 9/5C = 22 - 32 = -10$$
$$\therefore C = -10 \times 5/9 = -5.6°C$$

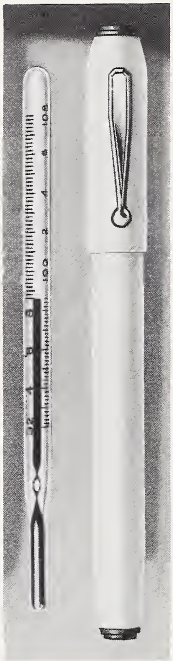


Fig. 17-5.
A clinical thermometer. Notice the short range of temperature and the constriction in the stem just above the mercury bulb.

Body Temperature

The internal temperature of the human body remains remarkably constant at about 98.6°F. However, a person does not have the same body temperature at all times; it varies slightly throughout the day. But, if a man's temperature differed by ten degrees from normal he would probably die.

During the heat of summer, the body has two ways of cooling itself so as to keep within reasonable range of normal temperature. First, a network of blood vessels near the surface of the skin expands on hot days. This allows more blood from the interior of the body to flow through these blood vessels and, in this way, heat inside the body is radiated out from the skin. Another cooling system is the evaporation of perspiration. As we shall learn in Chapter 19, water absorbs heat as it evaporates and the heat needed for this purpose is taken from the body.

There are a number of practical ways of making a house livable in summer so as to prevent these natural cooling devices from becoming overworked. The first is to keep out the sun and hot air by closing windows and drawing shades during the day. This is a practice long adopted in the tropics; it can make a difference of at least 10 degrees in the inside temperature. An electric fan will also aid evaporation of perspiration and cool the body. It is unwise, however, to aim an air blast directly at the body—this will give relief at the risk of a stiff neck. It is better to direct the hot air outside, particularly after nightfall, so that cooler air from outside enters the house through other openings.

Not all animals can maintain a constant body temperature; only birds and most mammals do this. These are called ***warm-blooded*** animals. ***Cold-blooded*** animals, such as insects, frogs, snakes and fish, obtain their body heat from external sources such as the ground, water or the sun. In this respect, they are like a stone or other inanimate object. During the winter, cold-blooded animals become so cold that they cannot live a normal life; they either die or hibernate. Insects, for instance, do not fly around during the winter, and the birds that feed on them must migrate to a warmer climate in order to find food.

A Clinical Thermometer

A clinical thermometer is used to determine the temperature of the human body. It has no other purpose so that only a short range of temperature is needed; actually it is usually a range of only 16 degrees, from 92°F to 108°F.

To read body temperature correctly, the mercury must remain in the stem after the thermometer has been removed from the mouth; that is, the mercury column must be prevented from falling before a reading is taken. This is accomplished by a constriction in the stem just above the bulb. When the mercury in the bulb is heated, the force of expansion is enough to drive the mercury past the constriction and up the stem. When it cools, however, the mercury column breaks at the constriction and is held in the stem so that a reading can be made. A sharp snap of the wrist is usually enough to force the mercury past the constriction and reset the thermometer.

After use, a clinical thermometer is usually sterilized by immersing it in alcohol. Hot water should not be used for this purpose since the force of expansion would first fill the stem with mercury and then break the thin wall of the glass bulb.

A Meat Thermometer

A meat thermometer has a range of about 100°F to 212°F and the temperatures for rare, medium, and well-done are clearly marked on the scale. The end of the thermometer is pointed so that it can be inserted into the roast. In this way, the temperature of the *center* of the roast is indicated on the scale.

An Oven Thermometer

A bimetal strip is usually used in an oven thermometer. A thermometer of this type is not as accurate as a mercury one but it is more compact and convenient. Moreover, mercury would be an unsatisfactory liquid because its boiling point (680°F) is near the temperature of a very hot oven.

The bimetallic strip in a thermometer is arranged as a coil, the metal with the greater expansion forming the outer surface of it. When the coil is heated, it expands and winds up. A pointer, attached to the coil, moves over a scale, and registers the temperature in degrees (see Fig. 17-5A).

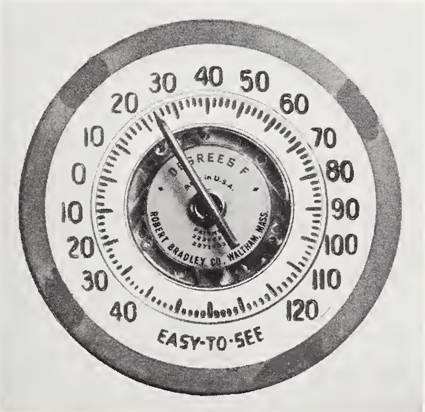


Fig. 17-5A. A dial thermometer uses a bimetallic coil to indicate temperature.

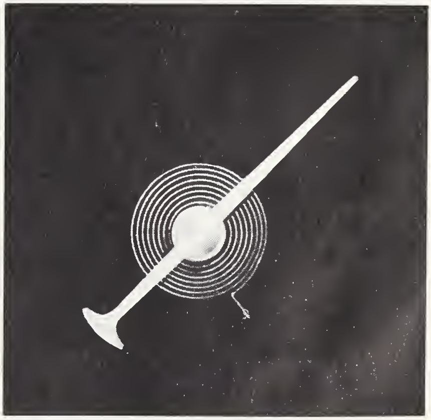


Fig. 17-5B. Temperature changes cause the coil to wind or unwind. This, in turn, rotates the pointer.

Mercury as a Thermometer Liquid

Most liquid thermometers contain mercury. What are the advantages of mercury which is expensive, as compared to, say, water which is cheap? Mercury expands regularly when heated. This is not true of water which, as a matter of fact, contracts as it is heated from 0°C to 4°C. Mercury is a metal and therefore a good conductor of heat. As a result, it readily assumes the temperature of the object it touches. Still other advantages of mercury are that it does not stick to glass like water and, finally, it is opaque and can be easily seen in the stem.

However, a liquid cannot be used to register temperatures near its boiling or freezing points. Why not? The boiling point of mercury is about 360°C (680°F), and its freezing point is about −40°C (−40°F). The upper limit of a mercury thermometer is high enough to cover most common high temperatures; indeed, it is a few degrees above the upper limit of the usual oven range. The lower limit, however, is well within the range of common low temperatures. Low winter temperatures in the prairie provinces are sometimes below the freezing point of mercury. For low temperature measurements, alcohol is a better liquid than mercury. The boiling point of alcohol is 78°C (172°F), but its freezing point is −112°C (−170°F). Since alcohol is transparent, a red or blue dye is usually added to make it visible.

Low Temperatures

Winter temperatures in the northern part of Canada are sometimes very low. A "zero" day is not uncommon (the term *zero* of course refers to the Fahrenheit temperature), and temperatures as low as −60°F have been recorded. In Siberia, probably the coldest habitation on earth, the temperature has been known to drop as low as −94°F (−70°C).

Temperatures much lower than "weather" temperatures have been obtained in the laboratory. Dry ice, which is made by freezing carbon dioxide gas, has a temperature of about −80°C (−112°F). Dry ice is used in refrigerator cars so that meat, vegetables, and fruit can be shipped without the risk of decomposition. It is also used to keep ice cream frozen. Another refrigerating agent, even colder than dry ice, is liquid air; its boiling point is about −200°C (−328°F).

As a substance is cooled, its molecular motions decrease in speed. The temperature at which molecules would cease to have any motion at all has been calculated. This is the ***absolute zero of temperature*** and its value is −273°C or −460°F. Absolute zero is the theoretical limit of low temperature. It is impossible to reach absolute zero in practice, although scientists have come within a few thousandths of a degree of it.

Recent experiments with rockets have yielded some interesting information concerning the temperature of the upper atmosphere. In the lower part of the stratosphere, about 10 miles up, the temperature is about −70°F (−57°C) and then, for some reason, the temperature rises to more than 1000°F in the ionosphere, about 150 miles up. However, at this altitude the atmosphere is exceedingly thin, far too thin for the heat to be felt. That is to say, although the molecules vibrate rapidly, there are too few of them to transfer much heat energy to an object.

High Temperatures

One of the hottest places on earth is Tunis, in North Africa, where a temperature of 118°F in the shade has been recorded. The highest temperature reached in New York City is 102°F (39°C). But even these high temperatures are relatively low when compared with the temperature of boiling water. In a higher range there are the melting points of rocks and metals. The temperature of molten volcanic lava is about 1100°C, the melting point of iron is about 1500°C, and the melting point of tungsten, the highest melting point of any metal, is 3370°C. The temperature of an oxyacetylene flame, and also of an electric furnace, is about 3500°C.

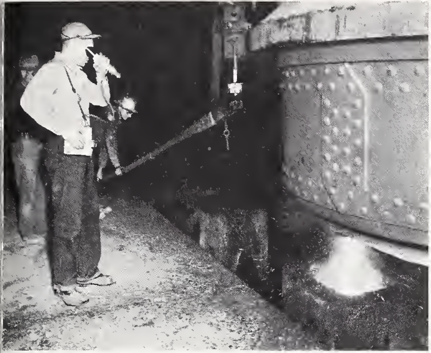


Fig. 17-6. A pyrometer. This man is checking the temperature of the molten steel as it is being poured into the ingot mold. The temperature (about 2700°F) is indicated by the color as seen through the pyrometer.

The temperature of stars is much higher, some having a surface temperature of 30,000°C. The surface temperature of the sun, a cooler star, is about 6000°C, but the interior temperature of the sun has been estimated at more than 10 million degrees centigrade. The highest temperatures on earth have been produced in nuclear reactions. An atomic bomb, at the moment of fission, has a temperature of over a million degrees centigrade, and in a thermonuclear reaction (a hydrogen bomb) the temperature reaches at least ten million degrees. Although there is a limit to low temperatures (the absolute zero), scientists have no knowledge of a theoretical limit to high temperatures.

Temperature and Color

It is a familiar observation that if a substance is heated strongly, it begins to glow. Any body, liquid or solid, begins to glow a dull red when its temperature is raised to about 1000°F. An iron bar, for example, first glows a dull red. As the temperature is raised, it becomes bright red-hot, then yellow-hot, and finally, white-hot. In other words, the color of a metal changes with its temperature and, if two different metals show the same color, they are at the same temperature. This color-temperature relation is used in the construction of high-temperature thermometers called pyrometers. A pyrometer is used, for instance, to find the temperature of molten steel in an open-hearth furnace. Even a copper wire, in a Bunsen flame, shows by its different shades of color that the flame varies a good deal in temperature.

Experiment

17-3. To show that the temperature of a Bunsen flame is different at different points

Light a Bunsen burner and adjust the air supply so that the flame begins to roar. Support one end of a copper wire in a cork stopper and then hold the wire across the base of the flame. Notice the two dull red patches on the wire. Slowly raise the wire up the flame and the wire shows patches of a brighter red. Just above the blue inner cone the wire glows yellow-hot. Now hold the end of the wire in this same region for a minute or so and a globule of molten copper collects on the tip. This is the hottest region of the flame.

Things to Remember

A *Fahrenheit degree* is equivalent to 5/9 of a *centigrade degree.* A *centigrade degree* is 9/5 of a *Fahrenheit degree.*

To change a *Fahrenheit temperature* to the corresponding *centigrade temperature,* subtract 32 from the Fahrenheit temperature and then multiply the result by 5/9.

The temperature of melting ice is 0°C (32°F) and of boiling water 100°C (212°F).

The *temperature of the human body* is 98.6°F (37°C).

Warm-blooded animals are able to maintain a constant body temperature; *cold-blooded animals* are not.

Absolute zero is the lowest possible temperature, –273°C (–460°F).

Questions

Part A

1. What is temperature?
2. Explain why the sense of touch is not a good temperature indicator.
3. What are the [**a**] centigrade and [**b**] Fahrenheit scales of temperature?
4. Give examples of [**a**] a "gas" thermometer, [**b**] a "liquid" thermometer, [**c**] a "solid" thermometer.
5. What is the essential difference between warm-blooded animals and cold-blooded animals?
6. Name the natural devices which cool the body on a hot day.
7. What is [**a**] body temperature, [**b**] the absolute zero of temperature?
8. How does an oven thermometer operate?
9. What is the liquid in a low-temperature thermometer? Why?
10. What is a pyrometer?

Part B

11. Explain why expansion can be used as a way of measuring temperature.
12. Describe Galileo's air thermometer and explain how it works.
13. Describe the essential steps in making a mercury thermometer.
14. Describe a clinical thermometer and explain how it differs from an ordinary mercury thermometer.
15. State some of the advantages of mercury as a suitable liquid in a thermometer. State a disadvantage.
16. The color of a hot metal can be used to indicate temperature. Explain why.

Problems

1. A copper bar is heated from 100°C to 200°C. Find the temperature change on [**a**] the centigrade scale, [**b**] the Fahrenheit scale.
2. A copper bar is cooled from 1000°F to 500°F. Find the temperature change on [**a**] the Fahrenheit scale, [**b**] the centigrade scale.
3. In a certain town, the highest summer temperature was 108 Fahrenheit degrees above the lowest winter temperature. What is this temperature range in centigrade degrees?
4. Compute the range of temperature in Fahrenheit degrees between the boiling point of mercury (360°C) and its freezing point (–40°C).
5. What Fahrenheit temperatures correspond to [**a**] 60°C, [**b**] –100°C?
6. What centigrade temperatures correspond to [**a**] 60°F, [**b**] –100°F?

7. A mixture of ice and salt may produce a temperature of 0°F. What is this on the centigrade scale?
8. The freezing point of mercury is –40°C. What is this on the Fahrenheit scale?
9. The boiling point of alcohol is 172°F. What is this on the centigrade scale?
10. What are the temperatures of dry ice (–80°C) and liquid air (–200°C) on the Fahrenheit scale?
11. The melting point of sulphur is 238°F. What is this on the centigrade scale?
12. Most rocks are molten at 2000°F. What is this as a centigrade temperature?
13. The temperature of molten lava is about 1100°C. Express this as a Fahrenheit temperature.
14. Compute the Fahrenheit temperature of the absolute zero (–273°C).
15. [**a**] Find the temperature on the other scale corresponding to (i) 77°F and (ii) –15°C.
    [**b**] Find the number of (i) centigrade degrees, (ii) Fahrenheit degrees between these two temperatures.

Things to Do

To make a thermometer from a bimetallic strip

Buy a cheap oven thermometer at a five-and-ten-cent store. Remove the metal coil from the thermometer. This is a stiff bimetallic strip, probably of brass and iron, with brass on the outside. Straighten out the coil and notice that one end (the inner one) is attached to a metal rivet. Rewind the coil into a spiral of about 1-inch diameter.

Fasten a small wooden post (about 3 inches tall) to a flat baseboard (about 9 inches long). Secure the spiral in a vertical plane to the top of the post by means of the rivet. Attach a light metal pointer to the other end of the spiral. Fasten a rectangular piece of cardboard to the baseboard in such a position that the end of the pointer is about halfway up the cardboard. The cardboard can now be used as a scale. Read the temperature of the room with a mercury thermometer and write this temperature (e.g. 75°F) on the cardboard near the end of the pointer. Place an electric light bulb near the coil. The rise in temperature causes the coil to unwind, and the pointer falls. Mark the end of the pointer on the cardboard. Let a mercury thermometer touch the coil. Read the temperature and then write it on the cardboard near the end of the pointer. Take the thermometer outside on a cold day. Notice that the pointer rises. Read the outside temperature by means of a mercury thermometer and write this temperature on the cardboard.

The thermometer is now complete–the movement of the pointer over the scale indicates temperatures that can be approximately guessed from the three points on the scale.

With ingenuity, the construction of the thermometer can be improved. For instance, a more rugged scale can be made by mounting a suitable piece of wood onto the baseboard.

18

What is Heat?

If we were asked to name the one factor that has contributed most to modern civilization, we would probably answer "Heat." Modern civilization really began when man learned how to make engines. In this way he used the heat from burning fuels to good purpose by making them do work for him. The work done by engines freed man from much unnecessary physical labor and, for the first time, the routine of his long working day could be relieved by leisure hours. What do we understand by heat?

What is Heat?

To answer this question, let us consider a few examples. Suppose we boil a kettle of water and then pour some of the water into a cup. If thermometers are placed in the kettle and cup they will indicate the same temperature. And yet we know that the larger quantity of water in the kettle contains more heat than the smaller quantity of water in the cup. What is the difference between heat and temperature? We have already stated that temperature is a measure of the average speed of the molecules of a substance. Hence the average speed of the water molecules is the same in the kettle as in the cup. But there are far more molecules in the kettle than in the cup. Hence we conclude that *the heat in a body depends on the number of molecules (that is, on the mass of the body) as well as on their speed.*

Let us take another example. When an automobile is stopped by applying brakes, friction between the brake shoe and the drum of the wheel develops heat. If the brakes are applied for some time, the heat of friction may burn out the shoe lining. It is clear from this example that the kinetic energy of the moving automobile has been converted into heat. In other words, heat is a form of energy.

If a bullet fired from a rifle is suddenly stopped by a steel plate, both bullet and plate become very hot and the bullet may even melt. When the bullet is stopped, its kinetic energy is transferred to the atoms of the bullet and plate. These atoms vibrate more rapidly and this effect is felt as heat.

To Measure Heat

Before we can measure the quantity of heat in a body, we must first agree upon a unit of heat. Since both temperature (the kinetic energy of the molecules) and the mass of an object (the number of molecules) determine the heat in a body, a unit of heat must include both these factors. A unit of mass is a pound, and a unit of temperature is a degree Fahrenheit, and the heat unit that involves both of these is called a ***British thermal unit***. It is defined as ***the quantity of heat needed to raise the temperature of 1 pound of water through 1 degree Fahrenheit.*** The British thermal unit is usually abbreviated to Btu. A *calorie* is the corresponding unit of heat in the metric system; in this case the mass of water is 1 gram and the rise in temperature is 1 degree centigrade. That is to say, *a calorie is the quantity of heat needed to raise the temperature of 1 gram of water through 1 degree centigrade.*

Which is the larger, a Btu. or a calorie? To express a Btu. in calories, we must convert 1 pound to grams (1 lb. = 454 gm.), and a temperature change of 1°F to the corresponding change in centigrade degrees (1 F° = 5/9 C°). Therefore,

$$\begin{aligned} 1\ \text{Btu.} &= \text{lb.} \times 1\ \text{F}^\circ \\ &= 454\ \text{gm.} \times 5/9\ \text{C}^\circ = 252\ \text{cal.} \end{aligned}$$

It is convenient to remember that a Btu. is approximately 250 times as large as a calorie.

As stated above, the heat needed to raise the temperature of water can be computed by multiplying the mass of the water by the rise in temperature. If the mass is in pounds and the temperature rise is in Fahrenheit degrees, the heat units must be expressed in Btu.'s; if the mass is measured in grams and the temperature in degrees centigrade, heat is expressed in calories.

Example 1. How much heat is needed to raise the temperature of 15 pounds of water from 50°F to 170°F?

$$\begin{aligned} \text{Heat} &= \text{Mass of water in lb.} \times \text{temp. change in F degrees.} \\ &= 15 \times (170 - 50) = 15 \times 120 \\ &= 1800\ \text{Btu.} \end{aligned}$$

Example 2. Compute the heat lost if 250 grams of water are cooled from 95°C to 20°C.

$$\begin{aligned} \text{Heat lost} &= \text{Mass of water in gm.} \times \text{temp. change in C degrees.} \\ &= 250 \times (95 - 20) = 250 \times 75 \\ &= 18{,}750\ \text{cal.} \end{aligned}$$

Example 3. Determine the final temperature if 20,000 calories of heat are put into 500 grams of water at 30°C.

Let t be the final temp. of water.

$$\text{Heat} = \text{Mass of water} \times \text{temp. change}$$

$$20{,}000 = 500 \times (t - 30)$$

$$\therefore \quad t - 30 = \frac{20{,}000}{500} = 40$$

$$\therefore \quad t = 40 + 30 = 70^\circ\text{C.}$$

Heat Capacity of Substances

Suppose we heat equal weights of water and earth, will the rise in temperature be the same in each case? This is an important question. Another way of asking the question might be: Does the sun heat up the sea and the land near the shore by the same amount? A simple experiment will give an answer to this question.

Experiment

18-1. To compare the heat capacity of sand and water

Pour 200 grams of water into one beaker and 200 grams of sand into another. Put each beaker on a tripod upon which a wire gauze has been placed. Hold a thermometer in each beaker and read the temperatures of sand and water.

Adjust the flames of two Bunsen burners so that they are small and, as nearly as possible, alike. Put a burner under each beaker and stir the sand vigorously (why?) and the water gently, throughout the experiment. Read both thermometers together after intervals of 1 minute. Record the temperatures and continue heating the beakers for 4 or 5 minutes.

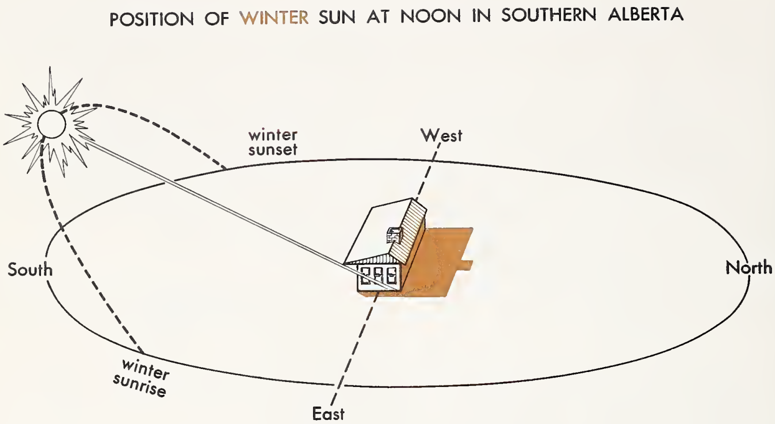


Fig. 18-1. The long overhang also allows the maximum of sunlight to enter the house in winter.

Which thermometer shows the greater rise in temperature? It should be clear from the data that the sand heats up more rapidly than the water. What is the significance of this? It means that water has a greater heat capacity than sand.

The smaller heat capacity of sand (or earth) explains why land heats up more than water near the sea shore on a hot summer day. You will recall that, as a consequence of this, a sea breeze blows during the day. At night both land and water radiate the heat they gained during the day. But, owing to its smaller heat capacity, the temperature of land falls more rapidly than that of water. In consequence, water becomes relatively warmer so that a land breeze is formed.

All substances have different capacities for absorbing heat. In other words, the amount of heat in a body depends not only upon its mass and temperature but also upon the nature of the substance itself. That is why in defining units of heat it is necessary to mention the particular substance—water—that is being heated.

Heat from the Sun

All life on earth depends on heat from the sun. The sun warms the earth, thereby producing a surface temperature which makes it possible for plants to grow and man to live. Without the sun's heat, the temperature of the earth would fall almost to absolute zero; neither plant nor animal life could exist.

Not only does the sun heat the earth directly, but all other sources of heat, except heat from nuclear reactions, come to us indirectly from the sun. Burning wood, coal, oil, or natural gas is a chemical reaction in which the sun's energy is released, and the heat we get from electricity also comes originally from the sun.

As stated in Chapters 12 and 13, coal, oil, and natural gas are fossil fuels; they are the remains of vegetation that thrived millions of years ago. This vegetation lived by storing heat energy from the sun (that is, by photosynthesis), and this stored energy is not released until the fuels are burned. It seems strange that the heat we get from coal is the same heat that was locked up ages ago. Electricity obtained from burning coal has, of course, the same origin. But even electricity from water power comes indirectly from the sun. The sun causes water to evaporate and the vapor may condense to clouds and then to rain. If the rain falls in a highland region it may form a stream or lake suitable as a source of water power.

Sunshine is one of our great natural resources, and the sun's heat offers an almost limitless source of power. Unfortunately, man has scarcely begun to tap it for industrial purposes because he has not yet found a satisfactory way to store it. In this respect he is far behind nature, and herein lies one of the most challenging problems of science.

Most of the sun's heat that strikes the earth eventually escapes into space and is lost. If man could use all the sunlight that falls on the earth, he would have no need for coal, or oil, or atomic energy. Even the amount of heat from a bright sun that falls on the roof of a house in one day is equivalent to the heat obtained by burning a tankful (12.5 gallons) of gasoline or a man's weight (150 pounds) in coal. The vast potential power in sunshine can also be expressed this way: the heat distributed over the earth from only three days of sunshine is as much as the heat that would be evolved by burning all the reserves of coal, oil, and natural gas in the earth.

All attempts to use this wasted energy on a large scale have so far failed. One difficulty is that sunshine is not continuous; there are many hours of darkness, and even in daylight the sun may be masked by heavy clouds. This means that the storage problem must be solved before sunshine can be used as a continuous source of energy. Some progress has already been made in this direction. For instance, a steam engine using a solar furnace can operate a generator, which can produce electricity which, in turn, can be used to charge storage batteries. But these need frequent recharging and are very expensive.

POSITION OF SUMMER SUN AT NOON IN SOUTHERN ALBERTA

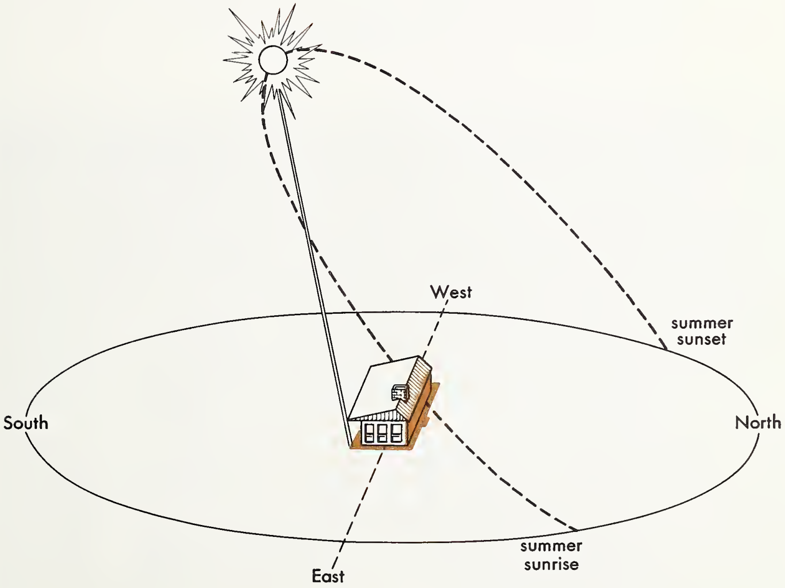


Fig. 18-2. The roof of a solar house has a long overhang which cuts off the direct rays of the sun in summer.

A Solar Furnace

One of the ways to catch sunlight for industrial use is to focus it by huge mirrors. In this way it is possible to reach temperatures high enough to produce steam to operate steam engines. One such mirror has a diameter of 30 feet and contains more than 3500 pieces of glass which concentrate the reflected rays of the sun into a solar furnace. A temperature of about 3000°C can be created at the focus, and a steel bar placed there would melt in a few seconds. A solar plant of this kind is expensive. A large mirror is costly and fragile; it must be kept free from dust, otherwise it loses its effectiveness; and it must have a mechanism that will enable it to rotate with the sun. Why?

Solar House Heating

Although solar furnaces have been slow to make their impact on industry, marked progress has been made in using the sun's heat to heat houses and to provide hot water for domestic use. Even in Canada, where winters are long and cold, solar houses have been operated with only a little help from coal or oil furnaces.

Two types of solar houses have been designed. In one type (see Fig. 18-1.) large windows facing south are installed and wide eaves project over them. The large windows are designed to admit maximum sunshine in winter, and the wide eaves give shade in summer when the sun is higher in the sky (see Fig. 18-2).

The second type (see Fig. 18-4) has a suntrap in the roof. This is usually a blackened metal absorber, placed on the southern slope and tilted at the right angle to absorb the maximum amount of heat during the winter. Pipes through which water circulates are installed under the blackened surface. From the pipes, the warmed water flows to an insulated storage tank, and then to the radiators. Actual tests have shown that, with a device of this kind, fuel costs can be reduced by as much as 50 per cent in regions of abundant winter sunshine.

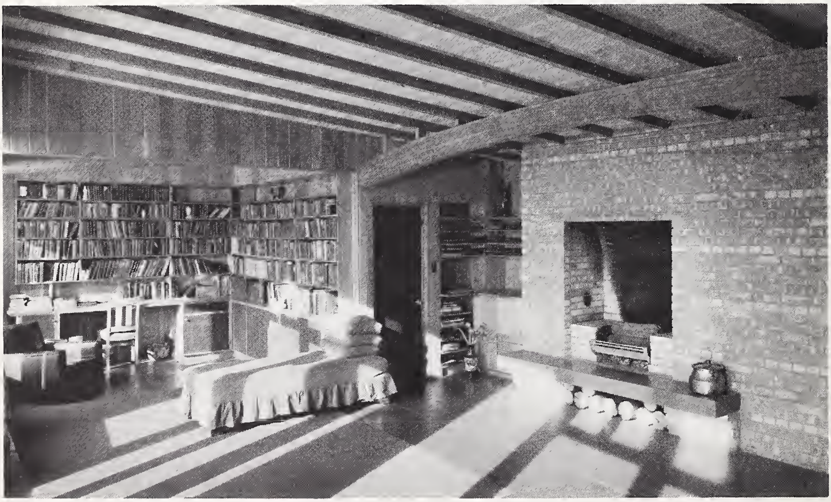


Fig. 18-3. The living room of a solar house. This photograph was taken at noon in midwinter. It shows that sunlight floods the living room.

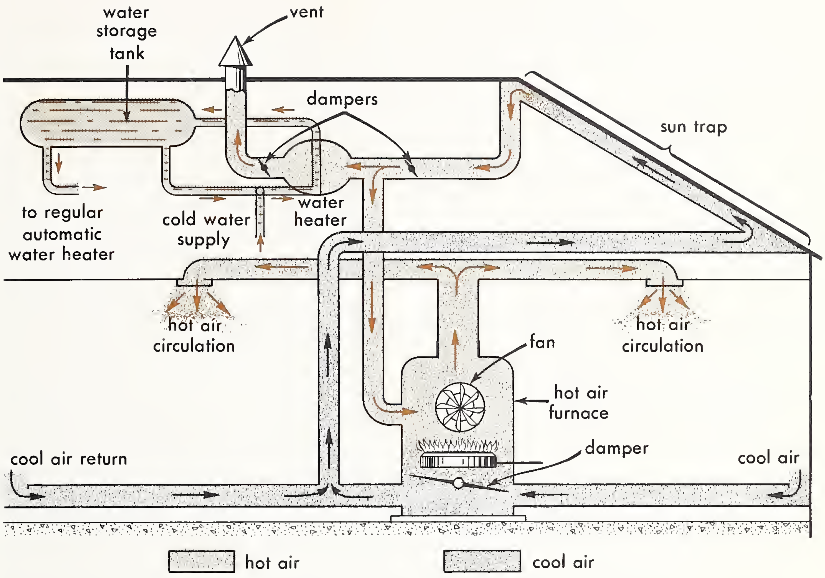


Fig. 18-4. A solar house with a suntrap in the roof.

Heat of Combustion

Most of the heat we use today is obtained from burning fuels. The combustion of gasoline in an automobile engine, for instance, provides the heat which expands the gases in the cylinder. These expanding gases then supply the force to move the car.

Different fuels have different heats of combustion as the accompanying table shows.

Substance	Heat of Combustion
Gasoline	19,000 Btu. per lb.
Hard Coal	14,000 Btu. per lb.
Wood	8–9,000 Btu. per lb.
*Coal Gas	600 Btu. per cu.ft.
*Natural Gas	1,000 Btu. per cu.ft.

*Since gases are measured by volume, their heat values are usually expressed in Btu.'s per cubic foot. The values of both coal gas and natural gas are approximately 20,000 Btu. per pound.

From this table we can conclude that if 1 pound of hard coal is burned, enough heat is released to raise the temperature of 14,000 pounds of water 1 degree Fahrenheit. Similarly, if 1 cubic foot of natural gas is burned, 10 pounds of water would be raised in temperature through 100 degrees Fahrenheit.

Foods also have a combustion value. Respiration is a combination of oxygen with products from the digestion of food. Respiration takes place in every one of the billions of cells in the body every moment of your life. During respiration a good deal of energy is released. It may be released as heat or as other forms of energy needed to maintain life processes and activities. The total amount of energy released in all these processes is approximately the same as the heat energy liberated if the food were completely burned in a fire.

The combustion values of foods are usually called ***heat values*** and they are expressed in ***large calories*** or ***kilocalories.*** A kilocalorie is 1000 times as large as a calorie as defined on page 173.

The heat values of a few common foods are shown in the accompanying table.

These values are expressed in kilocalories per ounce, and since there are 28.4 grams per ounce, the heat value per gram can easily be computed.

Food	Kilocalories per ounce	Food	Kilocalories per ounce
Apple	18	Egg	45
Beef	85	Ice Cream	60
Bread	72	Potato	25
Butter	210	Sugar	110
Carrot	12		

In Canada each person on the average eats a food equivalent of 3000 kilocalories a day and uses the equivalent of fifty times that amount (about 150,000 kilocalories) as heat and electricity. This quantity of heat energy is not available to much of the rest of the world. Indeed, for the world as a whole, the figures are 2400 kilocalories per person per day for food and only 6000 per day for heat and power. These statistics show that we in Canada are bountifully supplied in calories, amply in food, and lavishly in power. They also reveal a disparity between nations. That is why the trapping and storing of the sun's heat is a pressing world problem.

Things to Remember

The *temperature* of a body is a measure of the average kinetic energy of its molecules.

The *heat* in a body depends upon its mass, temperature, and the nature of the substance.

A *British thermal unit* (Btu.) is the quantity of heat needed to raise the temperature of 1 pound of water through 1 degree Fahrenheit.

A *calorie* (cal.) is the quantity of heat needed to raise the temperature of 1 gram of water through 1 degree centigrade.

1 Btu. = 252 cal.

The *heat of combustion* of a solid is the number of Btu.'s released when 1 pound of the solid is completely burned.

The *heat of combustion* of a gas is the number of Btu.'s released when 1 cubic foot of the gas is completely burned.

A *kilocalorie*, or large calorie, is 1000 times as large as a calorie.

Questions

Part A

1. Define the term *heat.*
2. Define the terms [**a**] British thermal unit, [**b**] calorie.
3. The heat of combustion of natural gas is 1000 Btu. per cubic foot. What does this statement mean?
4. [**a**] What is a kilocalorie? [**b**] Why are food values expressed in kilocalories rather than in calories?
5. One kind of solar house has a black metal suntrap. How does the black metal act as a suntrap?

6. The heat value of butter is 210 kilocalories per ounce. What does this mean?

Part B

7. Explain the difference between temperature and heat.
8. "Heat is a form of energy." Explain what this statement means.
9. A bullet fired from a rifle is stopped by a steel plate. Describe the energy transformations that take place.
10. What is meant by the term ***heat capacity***? How could you show by experiment that the heat capacity of water is greater than the heat capacity of soil?
11. State some of the difficulties to be overcome before the sun's heat can be used as a source of energy.
12. Briefly discuss two methods of heating solar houses.

Problems

1. How much heat is needed to raise the temperature of [**a**] 1 gram of water 30 centigrade degrees, [**b**] 12 pounds of water 1 Fahrenheit degree?
2. How much heat is produced in burning 1 ton of hard coal?
3. How much heat is needed to raise the temperature of [**a**] 15 pounds of water 30 Fahrenheit degrees, [**b**] 50 grams of water 65 centigrade degrees?
4. How many Btu.'s are equivalent to one kilocalorie?
5. How many kilocalories are needed to raise the temperature of 20 pounds of water 50 Fahrenheit degrees?
6. Steam raises the temperature of 10 pounds of water through 10 Fahrenheit degrees. Find the temperature rise in centigrade degrees if the same amount of steam is passed into 1 kilogram of water.
7. Compare the heat value of 2 pounds of bread, 2 pounds of carrots, 2 pounds of potatoes, and 2 pounds of apples with the heat value of 1 pound of butter.
8. Compute the heat value (in Btu.'s) of a tankful of gasoline (12.5 gallons) given 1 gallon equals 0.16 cubic foot and 1 cubic foot of gasoline weighs 42 pounds.
9. [**a**] How much heat (in Btu.'s) is needed to raise the temperature of 4 pounds of water from its freezing point to its boiling point?
   [**b**] Convert 4 pounds to grams, and then compute the heat in part [**a**] in calories.
   [**c**] From your answers in parts [**a**] and [**b**] calculate the number of calories per Btu.

Things to Do

Heat Insulation

Secure 4 similar tin cans about 2 quarts in size, and 5 similar ones about a pint in size. In each of the large cans place a small one. Pack absorbent cotton round one small can, excelsior round another, and steel wool round a third. Support the fourth small can with cork stoppers, leaving an air space between the small and large cans. The fifth small can should be supported on cork stoppers, but this is not placed in a larger can.

Cover the cans with a piece of cardboard through which a hole, large enough to admit a thermometer, has been bored. Nearly fill each of the small cans with the same quantity of hot water (almost boiling), replace the covers, and insert the thermometers. Take the temperature of the water in each can every five minutes, for an hour. Tabulate the readings.

What conclusions can you draw from the data? Which medium is the best heat insulator? Which is the poorest? Is a layer of air between the containers better than no layer at all?

19

Evaporation of Liquids

It is a matter of common observation that water left in an open dish eventually disappears; the liquid water changes to water vapor, a process called *evaporation*. Evaporation is a common phenomenon. It takes place on a small scale when perfume escapes from an open bottle; on a larger scale when gasoline vaporizes in an internal-combustion engine; and on a vast scale when the waters of lakes, rivers, and seas are changed to water vapor.

Evaporation, a Cooling Process

From experiments we learn that, whenever a liquid evaporates, the temperature of the liquid drops. This is an important observation. The simplest way to show this drop in temperature is to place some of the liquid on the bulb of a thermometer. This is done in the following experiment.

Experiment

19-1. Cooling by evaporation

Wrap some cotton around the bulb of a thermometer, and immerse the bulb in a bottle of rubbing alcohol or ether. Read the temperature. This reading is, of course, the temperature of the alcohol. Now withdraw the thermometer from the alcohol and again read the temperature. Notice that the temperature falls considerably. How can this be explained?

We have already stated that colliding molecules behave like billiard balls; some rebound with increased speed after collisions, others with decreased speed. Some of the faster moving molecules near the surface of the liquid are able to pull away from the attractive forces of neighboring molecules and escape from the liquid. This is the process of evaporation (see Fig. 19-1). As the faster moving molecules escape, the average kinetic energy of the molecules that remain as liquid decreases and therefore, the temperature of the liquid drops. And this is what we found in our experiment.

We can think of numerous examples of cooling by evaporation. You may be familiar with the cooling effect of alcohol rubbed on the skin. You may also recall that body temperature is controlled by the evapora-

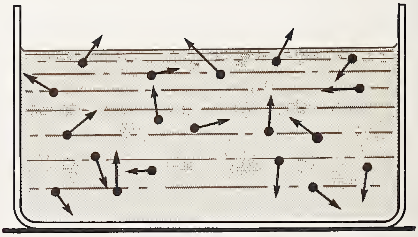


Fig. 19-1. Evaporation of a liquid. If the molecules near the surface move fast enough and in the right direction, they escape into the air.

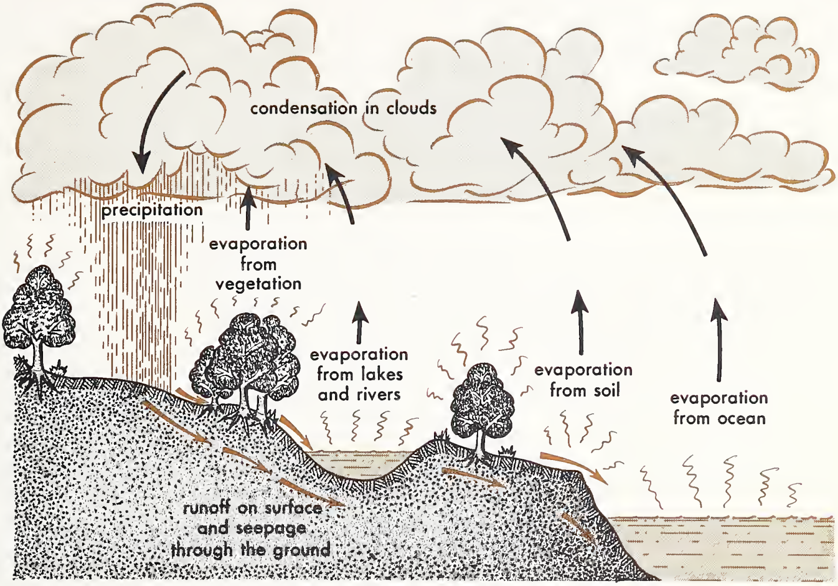

condensation in clouds
precipitation
evaporation from vegetation
evaporation from lakes and rivers
evaporation from soil
evaporation from ocean
runoff on surface and seepage through the ground

Fig. 19-2. The water cycle refers to the continuously repeated processes of evaporation of water and condensation of vapor.

tion of sweat. On a hot day, the pores of the skin open automatically, thereby allowing more moisture to escape from the sweat glands. The body is cooled by the evaporation of perspiration. That is, the skin supplies the energy needed to send water molecules from the skin to the air. Because the skin loses heat energy, it feels cool. On a cold day the reverse operation takes place; the pores close, evaporation is slowed down, and the heat of the body is conserved.

The Rate of Evaporation

The rate at which a liquid evaporates depends on the temperature of the liquid. Why is this? The higher the temperature of a liquid, the greater is the number of molecules with enough speed to escape from the liquid, and therefore the greater is the rate of evaporation. The rate of evaporation can also be increased by setting the air above the liquid surface in motion. That is why a fan is used to cool a room in summer. The moving air carries away molecules of water vapor and thereby makes it easier for other water molecules to escape from the skin. It should now be apparent that a warm breezy day is a good drying day for clothes.

The rate of evaporation also depends on the particular liquid as is shown in the following experiment.

Experiment

19-2. The different rates of evaporation of various liquids

Wrap some wick around the bulbs of 3 thermometers and immerse them in bottles of water, alcohol, and ether, one in each bottle. Read the temperatures. Now withdraw the thermometers, one at a time, and again read the temperatures. Notice that the temperature falls and then rises. How can this be explained?

You probably observed that the temperature drop was greatest for ether and least for water. We therefore conclude that ***rate of evaporation depends on the particular liquid.*** For instance, evaporation is rapid with ether, slower with alcohol, still slower with water and, with mercury, very slow indeed.

The Water Cycle

In nature, evaporation takes place on a vast scale; the heat of the sun evaporates almost 100,000 cubic miles (about 460,000,000,000,000,000 cubic tons) of water from the sea every year. What happens to all this water vapor? It is carried away by winds, condenses into clouds, and later falls to earth as rain. An almost incredible amount of rain falls to earth every day, or even every second of the day—about 15 million tons per second. The earth has been deluged at this rate for the past three billion years. Indeed, there is evidence to prove that during some geological periods the rainfall actually exceeded this rate.

The rain drains from the land, forming rivers and streams, and finally returns to the ocean where the process begins all over again. This continuously repeated process of evaporation of water and condensation of vapor is called the *water cycle*. It is the water cycle that makes soil productive and the earth habitable.

Refrigeration

The heat needed for the evaporation of a liquid may be supplied by an outside source such as another liquid. In this way, the second liquid may lose so much heat that it freezes. This is the basic principle of making artificial ice as is shown in the following experiment.

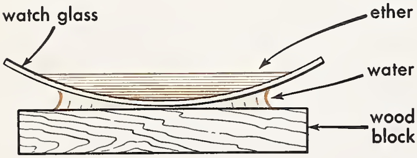


Fig. 19-3. When the ether evaporates, the water is frozen to ice.

Experiment

19-3. To make ice by evaporation

Place a few drops of cold water on a block of wood. Pour a little ether in a watch glass and place the watch glass in the water on the block. The arrangement is shown in Fig. 19-3. If the block is placed in a draft where ether can evaporate rapidly, the water becomes frozen to ice in a few minutes.

The same principle operates in the household refrigerator. Here a fluid is circulated around a closed circuit by a pump or compressor operated by an electric motor. Relatively few fluids are suitable because they must have some special properties. The fluid must be a gas at ordinary tem-

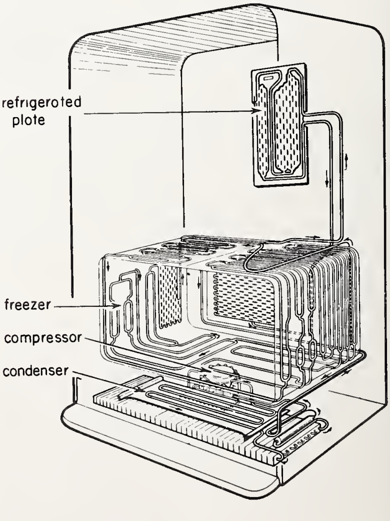


Fig. 19-4. The refrigerant liquid evaporates in the coils of the "freezer" and in doing so it takes heat from foods inside the refrigerator.

peratures and pressures; it must also be easily liquefied by a slight increase in pressure. Substances with these properties and commonly used in refrigerators are sulphur dioxide and Freon, whose rather forbidding chemical name is dichlorodifluoromethane. The circuit must also be supplied with mechanical devices that will provide both for evaporation of the liquid and condensation of the vapor. Evaporation, which absorbs heat, takes place inside the freezing unit; condensation, which evolves heat, takes place outside the refrigerating compartment.

When the interior of the refrigerator becomes too warm, a thermostat turns on the motor, which drives the pump. The pump compresses the gas which then flows through condensing coils where it condenses to a liquid, and, in doing so, it loses heat to the air in the kitchen. The liquid then flows through a tube to the expansion chamber which constitutes the cooling unit. Here the liquid is under less pressure so that it evaporates rapidly and, in evaporating, takes heat from the food inside the refrigerator. This, of course, is the vital step in the circulating process. The gas which results from the evaporation is then pumped out of the expansion chamber and again compressed and forced through the condensing coils, thus repeating the cycle of operations.

Fig. 19-5. This refrigerator has the same cooling system as that shown in Fig. 19-4.

Boiling

A simple and most instructive experiment is to heat water and watch it boil. Let us do this experiment and see what we can discover about this process.

Experiment

19-4. To boil water

Pour water into a 600-cubic centimeter beaker until about three-quarters full. Place the beaker on a tripod and heat it with a Bunsen flame. Now notice what happens. You should make at least four important observations: (1) Condensed vapor forms on the *outside* of the beaker, but it soon disappears. (2) Small bubbles appear in the water. Some stick to the bottom of the beaker, and some rise to the surface. (3) Larger bubbles form near the bottom of the beaker, but they vanish; these larger bubbles later rise some distance in the water before they vanish; and, finally, they rise to the surface and burst. The water is then said to be boiling. (4) If a thermometer is now held in the boiling water, the mercury rises to the 100°C mark and no further, no matter how long the thermometer is immersed in the boiling water.

Why the condensation on the *outside* of the beaker? You will recall that water vapor is one of the gases formed in a Bunsen flame. The water vapor condenses on the cold beaker but evaporates when the beaker is heated. It should be noted in passing that both water vapor and steam are invisible. What we see on the beaker are tiny droplets of water resulting from the condensation of the vapor. This is also what we see in a cloud in the sky, in the exhaust "steam" of a locomotive, or escaping from a tea kettle.

What are the tiny bubbles which stick to the bottom of the beaker and rise to the surface of the water? These are air bubbles. They were dissolved in water but a gas is less soluble in hot water than cold water. That is why air escapes from hot water. What are the larger bubbles that form near the bottom of the beaker and then disappear altogether? This question brings us to the problem of boiling.

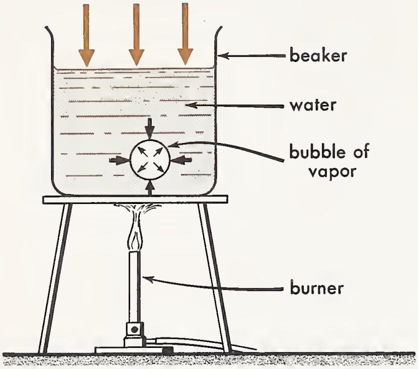


Fig. 19-6. Water boils when its vapor pressure equals the pressure of the atmosphere.

Why Water Boils

Some of the water at the bottom of the beaker changes to vapor when it is heated. This vapor forms bubbles and exerts an outward pressure inside the bubbles. The atmosphere, however, exerts an inward pressure, opposing the expansion of the bubbles (see Fig. 19-6). Since the first bubbles are crushed, we can conclude that atmospheric pressure is greater than the vapor pressure. As the water becomes hotter its vapor pressure increases and the bubbles grow larger. Finally, the water becomes so hot that its vapor pressure can withstand atmospheric pressure. The bubbles of vapor then rise to the surface where they burst. When this happens we say the water is boiling.

It should now be apparent that the boiling point of a liquid depends upon atmospheric pressure and this factor must be included in a definition of boiling point: ***The boiling point of a liquid is the temperature at which its vapor pressure equals the pressure of the atmosphere.*** If the barometric pressure is 30 inches (or 76 centimeters) of mercury, the boiling point of water is 100°C (or 212°F). At an elevation of 1 mile, the air pressure is only 26 inches (or 63 centimeters) and, as a result, water boils at 95°C (or 203°F).

Boiling under Reduced Pressure

If the pressure on a liquid surface is diminished, vapor bubbles can escape more readily. As a result, the boiling point of the liquid is lowered. In the following experiment, water is made to boil vigorously at temperatures well below 100°C by reducing the pressure on the water surface.

Experiment

19-5. To boil water under reduced pressure

Half fill a round-bottom pyrex flask with water. Heat the water to boiling and continue the boiling for 2 or 3 minutes to drive the air out of the flask. Stop the heating and, at the same moment, seal the flask tightly with a rubber stopper. Now invert the flask as shown in Fig. 19-7. Pour cold water onto the flask and notice that the water starts to boil. Pour more cold water on the flask and the water continues to boil even though its temperature is well below 100°C.

What diminishes the pressure in the flask? The cold water poured on the flask condenses some of the vapor. As a result, the pressure on the water surface is reduced and the boiling point is lowered.

Evaporation under reduced pressure is widely applied in the preparation of foods such as sugar, evaporated milk, dried eggs, dried fruits, and so on. For example, sugar crystals are formed by evaporating a hot syrup. The sugar would be scorched if the solution were boiled in an open pan. To prevent this, the syrup is boiled in a vacuum pan (a device for heating a liquid under reduced pressure), the temperature of boiling is thereby lowered and scorching is prevented. For the same reason, many dried fruits are prepared in vacuum pans by evaporation at reduced pressures.

Altitude and Boiling Point

We have already stated that atmospheric pressure decreases with altitude; the pressure at a height of 3.5 miles is only one-half the pressure at sea level. How does altitude affect the boiling point? The elevation of Denver in Colorado is about 1 mile above sea level. Here the pressure of the atmosphere is 63 centimeters and the boiling point of water is about 95°C. The elevation of Mount Robson in the Rockies is about 13,000 feet. Will water on the summit of Mount Robson boil at a higher or lower temperature than 95°C?

At high elevations, as in the city of Denver, the housewife has to contend with low pressures at all times and a cooking problem arises. Since water boils below 100°C, food must be cooked for a longer time than at sea level. Thus an egg boiled for four minutes in Toronto would, in Denver, have to be boiled for five minutes to make it just as hard. A housewife can solve this problem by using a pressure cooker, a device that raises the boiling point of water.

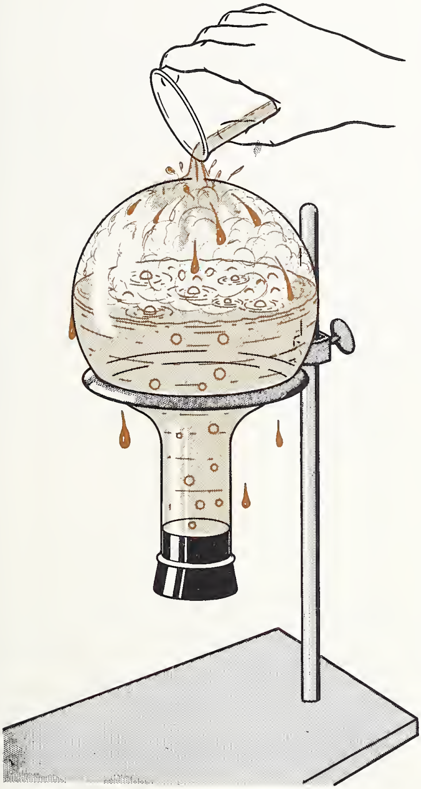


Fig 19-7. Hot water in a flask under reduced pressure can be boiled by pouring cold water on the flask.

Boiling under Increased Pressure

It should now be apparent that the boiling point of a liquid can be raised by increasing the pressure on the liquid surface. In a steam turbine, for example, the pressure is so high that the temperature of the steam (and of the boiling water) is above 300°C.

A pressure cooker is the most familiar device for raising the boiling point of a liquid. Raw food is placed in the cooker, a little water is poured in, and the lid is firmly fastened so that the cooker is airtight. The cooker is then heated. The water boils and the pressure of the vapor is thereby added to the pressure of the air inside the cooker. As the pressure increases, the boiling temperature of the water rises. Eventually the steam reaches a certain pressure and begins to escape through a safety valve. The temperature has then reached its maximum value; it rises no further.

A pressure cooker not only solves the cooking problems at high altitudes but it greatly reduces the time of cooking at any altitude. For instance, if the pressure in the cooker is 30 pounds per square inch (which is twice normal atmospheric pressure) the boiling point of water is raised to about 120°C (or 248°F) and the time of cooking is reduced by at least 50 per cent. The time taken to cook potatoes, for example, is normally about half an hour but this is reduced to only 10 minutes in a cooker that gives a pressure of 30 pounds per square inch.

Heat of Vaporization

As stated earlier in the chapter, if water in a beaker is heated, the temperature rises, and the water boils at 100°C. Once the water is boiling, however, its temperature does not rise above 100°C no matter how long it is heated. Nor will the temperature rise even if the water is heated more strongly. Stronger heating will merely increase the rate at which bubbles form and, in consequence, the rate of evaporation will increase. In other words, vegetables cannot be cooked any faster by boiling the water more rapidly; rapid boiling only results in a waste of fuel.

What happens to this heat put into boiling water? This heat energy is clearly associated with a change of state from liquid to vapor. It is called ***heat of vaporization.***

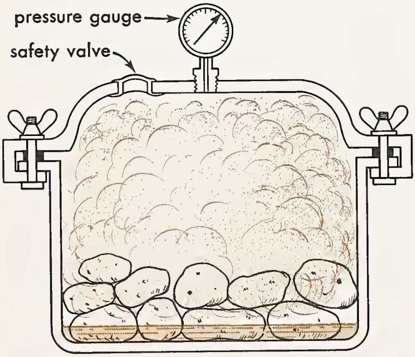


Fig. 19-8. Potatoes can be cooked in 10 minutes in a pressure cooker.

Latent Heat

When water changes to vapor there is a large increase in volume. For example, one cubic inch of boiling water becomes almost 1700 cubic inches of steam. Hence, during this change of state, the distances between the molecules are greatly increased. But, you will recall, molecules attract each other, and therefore work must be done to push them apart. And, to do work, energy must be supplied. The energy supplied for this purpose is heat energy.

Since the temperature of steam is the same as the temperature of boiling water, there is no change in the kinetic energy of the molecules. That is to say, the average speed of the molecules of boiling water is the same as the average speed of the molecules of steam. We therefore conclude that, in boiling, the heat energy is stored in the molecules as potential energy (the greater the distance between the molecules, the greater is their potential energy.) An increase in potential energy (unlike an increase in kinetic energy) does not involve an increase in speed. Hence there is no rise in temperature and therefore it cannot be indicated by a thermometer. For this reason the heat needed to cause a change in state from liquid to gas is called *latent* heat. (The word *latent* is derived from a Latin word meaning "hidden.")

Latent Heat is Released during Condensation

What happens if the process is reversed? That is to say, what happens if steam at 100°C is condensed to water at 100°C? In condensing, steam molecules become packed together. That is, they lose their potential energy and this potential energy is transformed into kinetic energy or heat. Because energy is always conserved (neither created nor destroyed), precisely the same amount of latent heat is released during condensation as was absorbed during evaporation.

Steam Heating

The most familiar example of losing heat by condensation is steam heating, a topic already referred to on page 159. In this system, steam, under pressure, is forced through pipes to all parts of a building. The steam condenses in the radiators and, as it does so, releases its latent heat (see Fig. 19-9). The condensed steam then returns to the boiler as hot water, where it again evaporates, picking up its latent heat from the burning fuel. And so the cycle of latent heat changes is repeated indefinitely.

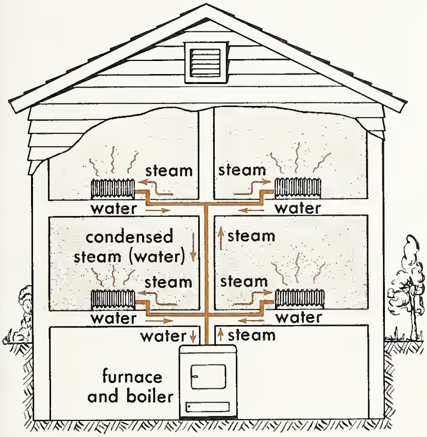


Fig. 19-9. In a steam-heating system, steam condenses in the radiators and releases latent heat.

Relative Humidity

The cooling caused by the evaporation of water from our bodies can make life more tolerable on a hot summer day. But on a muggy day there is scarcely any cooling effect, even if the air is circulated by a fan. Why is this? On a muggy day ***humidity***, or the amount of water vapor in the air, is high and, as a result, evaporation is retarded.

Or let us think of the humidity of the air immediately after a heavy spring shower. Due to evaporation of water on the ground, the air is almost completely saturated with water vapor. Further evaporation cannot take place, and clothes put out to dry stay wet. Suppose that the sun comes out and the temperature rises considerably. What of the humidity now? As warm air can hold more moisture than cold air, the atmosphere is no longer saturated with moisture. Evaporation can now take place, and clothes on the line begin to dry.

The important thing to note is that the *actual* amount of moisture in the air is the same in each case. At the higher temperature, however, the amount of water vapor in the air is less than the air can hold; that is, the ***relative*** amount of moisture is less at the higher temperature because the air is further from its saturation point. ***Relative humidity*** is a particularly important concept in meteorology. It means the ratio of the amount of water vapor in the air to the maximum amount of vapor the air can hold at that temperature. Or,

$$\text{R.H.} = \frac{\text{water vapor actually present in air}}{\text{maximum amount possible at that temperature}}$$

Relative humidity is usually expressed as a percentage; that is, the result obtained from the formula is multiplied by 100. A relative humidity of 100 per cent means that the air is saturated with water vapor. If warm moist air from outside (with a relative humidity of, say, 80 per cent) enters a cold house, it becomes saturated and moisture begins to condense on the walls and pipes. Suppose, on the other hand, that cold air from outside enters a heated house in winter. This cold air contains little moisture because little evaporation takes place in winter. When this air enters a heated room its relative humidity is still further decreased. Why? A relative humidity of 30 per cent, or even 20 per cent, is not uncommon in steam-heated houses kept at 75°F in winter. This is the relative humidity one might expect in the Sahara Desert. A low humidity is harmful. It causes furniture to dry out and fall apart.

It also causes the skin to become uncomfortably dry. A high relative humidity as experienced in the summer is equally harmful; it causes doors and drawers to swell and stick.

Experience has shown that, for comfort, the relative humidity should be between 40 and 60 per cent when the temperature is about 70°F. This is best achieved by air conditioning, particularly in winter. The problem of humidifying air is not a simple one. Several gallons of water would have to be evaporated every day, even in a small house, to maintain a humidity of 50 per cent. A modern air-conditioning system, however, adds the right amount of water to the air in winter and removes moisture from the air when the relative humidity is too high in summer.

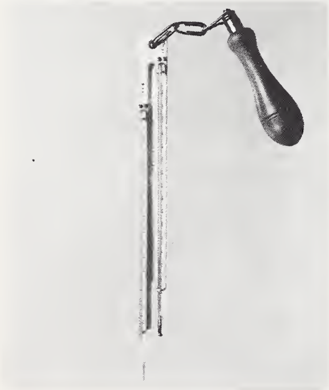


Fig. 19-10. A psychrometer sling is a wet- and dry-bulb hygrometer that can be whirled around for quick readings of the moisture in the air.

The relative humidity may be found by a wet- and dry-bulb thermometer (a hygrometer). This consists of two Fahrenheit thermometers supported alongside each other as shown in Fig. 19-10. The "dry-bulb thermometer" is an ordinary thermometer which indicates the temperature of the air. The bulb of the "wet-bulb thermometer" is covered by wet fabric from which evaporation takes place. Will there be any difference in the readings of the thermometers? Why? The wet-bulb reading will be lower than the dry-bulb reading and the difference between the two temperatures will depend on the condition of the air. If the air is dry, evaporation from the wet fabric is rapid, and the temperature difference between the thermometers will be large–it may be as much as 20°. If the air is damp, evaporation is slow and the difference will be small. If the thermometer readings are applied to a table of values supplied with the thermometer, the relative humidity of the air can be determined.

Dew Point

Suppose some air has a relative humidity of 70 per cent. If the air is now cooled, the relative humidity rises. Why? Eventually, if the air is cooled to a low enough temperature, it will become saturated. If the air is cooled below this temperature, it cannot hold all the water vapor present in the air and condensation begins; drops of liquid water begin to form on surfaces exposed to the air. The temperature to which a given sample of air must be cooled to become saturated and start condensation is called ***the dew point.***

Condensation often occurs when the humidity is high. For example, a glass of ice water on a moist summer day becomes covered with drops of water. Why is this? The air near the glass is chilled and, at the dew point, moisture begins to condense on the glass. A similar effect causes dew to condense on blades of grass on a cool summer night when humidity is high. Blades of grass rapidly lose heat by radiation. As a result, air near the grass is chilled and, when the dew point is reached, moisture from the air is deposited on the grass.

Things to Remember

Evaporation is a cooling process.

The *rate of evaporation* of a liquid increases as the temperature rises.

The *boiling point of a liquid* is the temperature at which its vapor pressure equals the pressure of the atmosphere.

The *boiling point* of water can be (1) *raised* by increasing the pressure on the water surface, (2) *lowered* by reducing the pressure on the surface.

Latent heat is the heat needed to cause a change in state.

Latent heat is *absorbed* during evaporation and *released* during condensation.

$$\text{Relative humidity} = \frac{\text{water vapor present in air}}{\text{water vapor needed to saturate air at that temperature}}$$

Dew point is the temperature at which water vapor in the air begins to condense.

Questions

Part A

1. What is evaporation?
2. On a hot day the body is cooled by perspiration. How?
3. What is a good "drying" day? Why?
4. What happens in the freezing compartment of your refrigerator?
5. [**a**] Define the boiling point of water.
   [**b**] What is the main difference between boiling and evaporation?
6. Will the boiling point of water be highest or lowest [**a**] on a mountain top, [**b**] at sea level, [**c**] down a deep mine? Why?
7. Explain the meaning of the term *latent heat.*
8. Define [**a**] relative humidity, [**b**] dew point.

Part B

9. Explain why evaporation is a cooling process.
10. Explain what is meant by the water cycle in nature.
11. Explain how and why artificial ice may be formed by evaporation.
12. Describe an experiment to show that water can boil at temperatures below 100°C. Why is this possible?
13. What is a pressure cooker? How does it operate?

14. Explain clearly why the temperature of boiling water does not rise if it is heated. What happens to the heat energy put into the boiling water?
15. Explain the principle of steam heating. What happens in a steam radiator?
16. In an electric refrigerator, latent heat is both evolved (given out) and absorbed (taken in). Explain what this means.
17. A large difference between the readings of a wet- and dry-bulb thermometer indicates a low relative humidity. Explain why.

Things to Do

Cooling by evaporation

Tie a wad of absorbent cotton over the bulbs of each of two thermometers. Read the thermometers. Dip one bulb into water and the other into rubbing alcohol. Move the thermometers rapidly back and forth a dozen times or so. Read the thermometers. What do the temperature changes indicate?

UNIT

V

Light

20

Illumination

The story of the development of light sources is remarkably similar to the story of the development of power. Early sources of artificial light were crude and inefficient, but they slowly improved as man came to understand the nature of light, just as man's early, crude devices for harnessing power have improved in convenience and efficiency.

There is, however, an outstanding difference between the development of light and the development of power. In early times man had to harness winds and running water to do work for him. However, light needs no harnessing—it comes as a free gift from the sun. But the sun gives light for only part of the day. In early times, therefore, nearly all human activity took place between the rising and setting of the sun. As civilization progressed, man invented means of producing light which could be used during the hours of darkness.

Sources of Light

Light has always been obtained indirectly as a result of producing heat, usually through the combustion of a fuel; the heat is, of course, an unwanted and wasteful by-product in the production of light. When scientists solve the problem of producing light, cheaply and conveniently, without heat, there will be a great saving of fuel.

Nature has already found a way of doing this. Fireflies give off light without heat. So do certain minute organisms in the sea that produce phosphorescence which can be seen on dark, moonless nights. Man has learned how to mix certain chemical compounds to produce a similar effect, but the process is inconvenient and expensive,

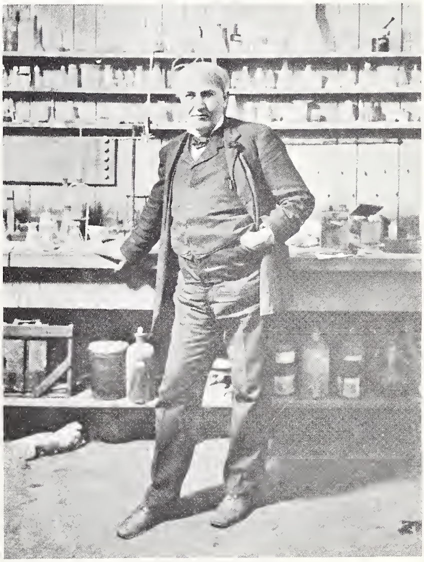


Fig. 20-1. Thomas Edison in his laboratory, about 1906. He had invented the incandescent lamp twenty-seven years earlier.

Fig. 20-2. Man's activity is no longer limited to daylight hours. New York at night is ablaze with artificial light.

and it does not give a light strong enough to be useful.

For centuries, the most common portable lights were burning sticks. Pine pitch on the end of a stick made the flame brighter, and it lasted longer. Many of the old castles in Europe used pine torches as late as the fifteenth century.

The Greeks and Romans used oil lamps, shallow dishes containing oil extracted from olives. These lamps gave a small flickering flame and little light. Moreover, an unpleasant odor accompanied the burning of olive oil.

Eventually, candles were invented. Candles were often made from tallow, or sheep fat. They were used to give light in coal mines before the Davy safety lamp was invented. In New England the early settlers made candles out of the wax from bayberry bushes which grow abundantly in that region. Today candles find little use except for decorative and religious purposes. Lighting was often one of the great lacks in early pioneer life in America. Abraham Lincoln had to study by the light of a fire because he had no candles or lamps.

Coal gas was first used for lighting about 1820. Although a special burner was used, coal gas was unsatisfactory as a source of light–it gave a sooty and yellowish flame. Whale oil extracted from the fat of whales was used in North America and other parts of the world as a fuel for lamps; these lamps were much superior to candles.

About 1850 the kerosene lamp was invented, a great improvement over both candles and whale-oil lamps as a source of light. The invention of the kerosene lamp resulted in a demand for petroleum which, in turn, led to the drilling of the first oil well in 1858. Today, of course, only a tiny fraction of the petroleum produced is used for lighting purposes, since electric lights are now almost universally used.

Both gas lamps and kerosene lamps can be made to give more light by surrounding the flame by a thin gauze mantle made of thorium and cerium oxides. These substances, when heated, give off a brilliant white light and make the lamps more efficient. Such lamps are still used in places where electricity is unavailable.

The Development of Electric Lighting

The first successful electric light, the carbon arc, was invented by Sir Humphry Davy in 1825. The light produced by a carbon arc is so bright that the eyes must be protected from the glare by dark glasses, if it is viewed directly.

Experiment

20-1. Making a carbon arc

Obtain two sticks of carbon and grind the ends to a point on coarse sandpaper. Mount the rods in clamps on separate ringstands. Insulate the carbon rods from the clamps by wrapping strips of asbestos around the rods. (*Caution: Do not touch*

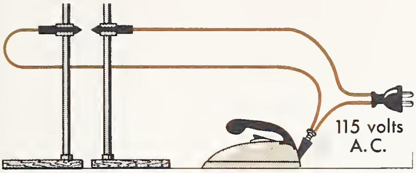


Fig. 20-3. A simple carbon arc can be made from two old battery carbons mounted on stands and connected as shown. *Caution*: Always use dark-colored glass when looking at the light.

both rods or ringstands at the same time, as the difference in voltage between them can give you a dangerous shock.) Connect the rods with wires in series with an electric iron or electric hot plate which serves as a resistor to limit the amount of current passed by the arc. The arrangement is shown in Fig. 20-3. Connect the whole apparatus to an electric outlet and then, by moving one of the stands, bring the two carbons together until they touch. When the points of contact become red-hot, the ends can be separated slightly to form a bright carbon arc that is white-hot. The light is produced by incandescent (white-hot) particles of carbon between the electrodes. The arc can be blown out by a good puff of air.

Carbon arcs were used for many years in street lighting; their great disadvantage was that they had to be continually adjusted as the carbons were used up.

A Carbon Filament

A carbon arc was not well suited for home use, and in its place Thomas Edison experimented with a long thin thread, or ***filament***, of carbon. He spent many years trying to find a suitable kind of carbon filament, and in 1879 he finally made a successful one out of bamboo fiber. The fiber was partly oxidized in a hot oven to turn it into carbon; it was then mounted in a glass bulb and the air was removed from the bulb. Why? The carbon-filament lamp, as it was called, was widely used for many years. Its disadvantage was that the carbon filament was very fragile, and it was eventually replaced by tungsten. A model of an early Edison lamp is shown in Fig. 20-4.

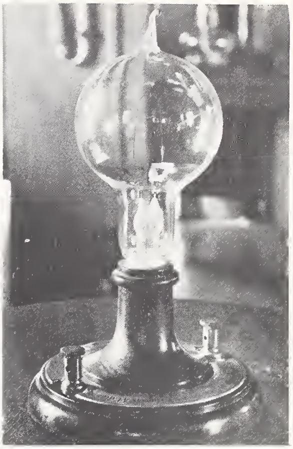


Fig. 20-4. A replica of the original filament lamp made by Edison in 1879.

A Metal Filament

The melting point of tungsten is above 3000°C, so it can be made white-hot by an electric current without fear of melting. However, the filament must be long and thin. Wire leads carry electricity to the tungsten filament. These leads are sealed into the glass bottom of the bulb, and the entire glass bulb is cemented into a screw plug. For some lamps the tungsten wire must be drawn so fine that a single pound of tungsten is drawn into 40 miles of wire.

It was found that tungsten filaments would last longer if, instead of being evacuated, the lamps were filled with nitrogen or argon gas. In a vacuum, evaporation of the hot filament causes a black deposit of tungsten to form on the inside of the bulb. This reduces the amount of light that can get through the glass. Moreover, evaporation makes the filament thinner until it finally breaks. The pressure of the nitrogen reduces evaporation so that more current can be passed through the filament which, in turn, raises its temperature. The higher the temperature, the whiter and brighter is the light and the greater the fraction of electrical energy converted into light energy. Thus more illumination is produced at a lower cost. In 1879 light from electricity cost about 30 times as much as it does today. The improvements made in the design of light bulbs are responsible for much of the decrease in cost.

Experiment

20-2. Examination of an incandescent lamp

Obtain a 200-watt clear-glass bulb of modern make. Examine the construction of the lamp, especially the filament and its supports, as shown in Fig. 20-5. Can you find the exhaust tube through which the air was pumped out and the argon let in?

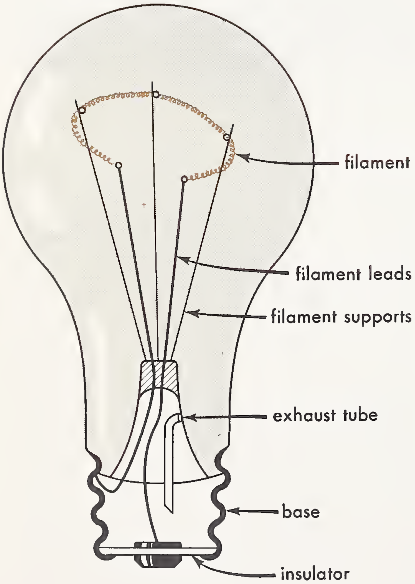


Fig. 20-5. A gas-filled tungsten lamp with a coiled filament.

Hold the bulb in a heavy towel and, with a sharp file, make a scratch about an inch long around the glass near the base. Screw the lamp into a socket and turn on the electricity. When the lamp is hot, drop a little water on the scratch. The glass should crack all the way around without disturbing the filament, which continues to glow. After a few seconds, a white cloud of tungsten oxide begins to form inside the bulb as the argon is slowly replaced by air. Finally, turn off the electricity, remove the glass, and examine the filament under a strong magnifying glass or a low-power microscope. Careful examination shows that the filament is really a fine coil of fine tungsten wire. Break open the metal base of the lamp to find where the filament is connected to the metal base.

Designing modern tungsten bulbs illustrates an important phase of an engineer's job. A design engineer must always be concerned with producing more efficient bulbs, but he must also consider the cost of electric lighting to the consumer. For instance, it is possible to design a bulb to operate at a high temperature with very high efficiency (that is, one that gives a large amount of light energy from a given amount of electrical energy). This, of course, results in a reduction in the cost of electric lighting. However, at a very high temperature, evaporation of the filament proceeds very rapidly, and the bulbs burn out so fast that the cost of new bulbs becomes greater than the saving due to increased efficiency. If, on the other hand, the filament is designed to operate at a low temperature, the efficiency is so low that even though the bulbs last a very long time, the cost of electric lighting is very high. Thus the design engineer must compromise between long life and efficiency in order to give the consumer electric lighting at the lowest cost.

Vapor Lamps

One of the newest sources of light is the vapor lamp, in which an electric current passes through a gas. Glowing gases produce much less heat than ordinary tungsten filament lamps.

Experiment

20-3. Light from gases

Wrap a piece of asbestos around the top of a Bunsen burner and tie it in place. Then slip it off carefully and soak it in a strong solution of table salt. Wipe off any excess solution, replace the asbestos on the burner, and light the gas. After a moment a bright yellow flame is produced. Turn out all white lights and examine your hands and your classmates' faces in the yellow light. Can you explain the results?

Soak other pieces of asbestos in strontium chloride and copper chloride. What colors are produced when these are heated?

Light is produced in a substance when the electrons in its atoms are disturbed. When atoms are packed closely together, as in a solid or a liquid, the easiest way to disturb the electrons is to heat the substance. When atoms are in the vapor form, however, their electrons can easily be disturbed by other fast-moving electrons, that is, by an electric current which is a flow of electrons. That is why a current causes a gas to glow.

Mercury vapor gives a greenish-white light that changes the color of ordinary objects. Such lights, however, are often used in factories where careful machine work is being done, since the color enables even poor eyes to see better. The invisible ultraviolet light given off by mercury vapor causes certain chemicals to emit white light. This is the basis of fluorescent lighting.

Fluorescent tube lighting is used in many industries, schools, and offices. This lighting is popular in the modern home. Fluorescent tubes are very efficient, are fairly cool, and their cost of operation is small, although their initial cost is high.

What is a fluorescent tube and how does it give light? A glass tube is coated on the inside with a powder which glows under ultraviolet radiation. The ultraviolet rays come from mercury vapor resulting from the evaporation of a small amount of mercury that is in the tube.

At each end of the tube there is a small tungsten filament (see Fig. 20-6). When the light is first turned on, an electric current heats these filaments which in turn heat the mercury vapor molecules near the filaments. As soon as enough mercury vapor becomes hot enough, the vapor can conduct electric current along the full length of the tube. The filament automatically goes out and the electric current flowing the length of the tube causes the mercury vapor in the tube to emit ultraviolet light which is absorbed by the fluorescent coating, causing it to give off an intense glareless white light restful to the eyes. The color of the light can be changed by coating the tube with various chemical salts.

A fluorescent light is cheaper to operate than an incandescent tungsten light; for example, a 40-watt fluorescent tube will produce about the same amount of light as a standard 150-watt incandescent bulb.

A ***neon light*** is another gas tube which uses electricity to produce light. Neon glows with a red color when an electric

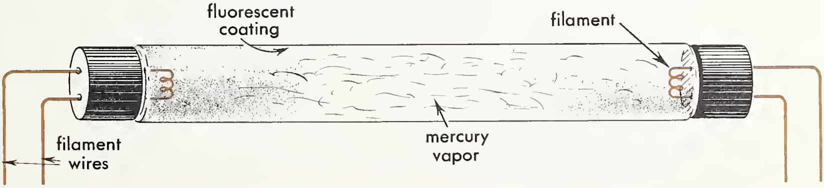


Fig. 20-6. A fluorescent light. The invisible ultraviolet light from the mercury vapor in the tube is absorbed by the coating on the inside of the glass. This coating then emits visible white light.

current flows through it. Neon lights are made in many shapes and designs; they are especially useful in making signs and decorations. The cost of operation is quite small, as you might expect from seeing many store neon signs in operation both day and night.

Sodium vapor lamps are very useful for highway lighting. They consist of glass tubes with tungsten filaments and small pieces of pure sodium. Electricity heats the filaments which in turn vaporize the sodium. This vapor conducts an electric current, giving off a soft yellow light.

Things to Remember

Kerosene lamps were invented in 1850.

Edison invented the *carbon-filament* lamp in 1879.

Modern incandescent lamps have a *tungsten filament* and are filled with an *inert* gas.

Vapor lamps produce light by passing an electric current through a gas.

Questions

Part A

1. What are the chief disadvantages of kerosene lamps?
2. Describe the development of electric filament lamps.
3. Why is nitrogen gas used in modern filament lamps?
4. What is a thorium oxide gas mantle used for?
5. How does the light output of a vapor lamp compare with that of an incandescent filament lamp using the same amount of electric power?
6. What are the advantages and disadvantages of a carbon arc lamp?
7. State two advantages of the tungsten-filament lamp over Edison's carbon-filament lamp.

Part B

8. How does a fluorescent lamp differ from a neon lamp in its production of light?
9. State one reason why a fluorescent lamp is more efficient than a lamp with a hot filament.

Things to Do

Using a gas mantle as a source of bright light

Hold a gas mantle (available at any hardware store) in a Bunsen flame or in the flame of a gas stove with a pair of tongs or tweezers. Do you get more light from the same amount of gas? What color is the light? Is it a better color for illumination than the gas alone? (*Caution: After the mantle has first been heated, it is very brittle and fragile.*)

21

Light and its Effects

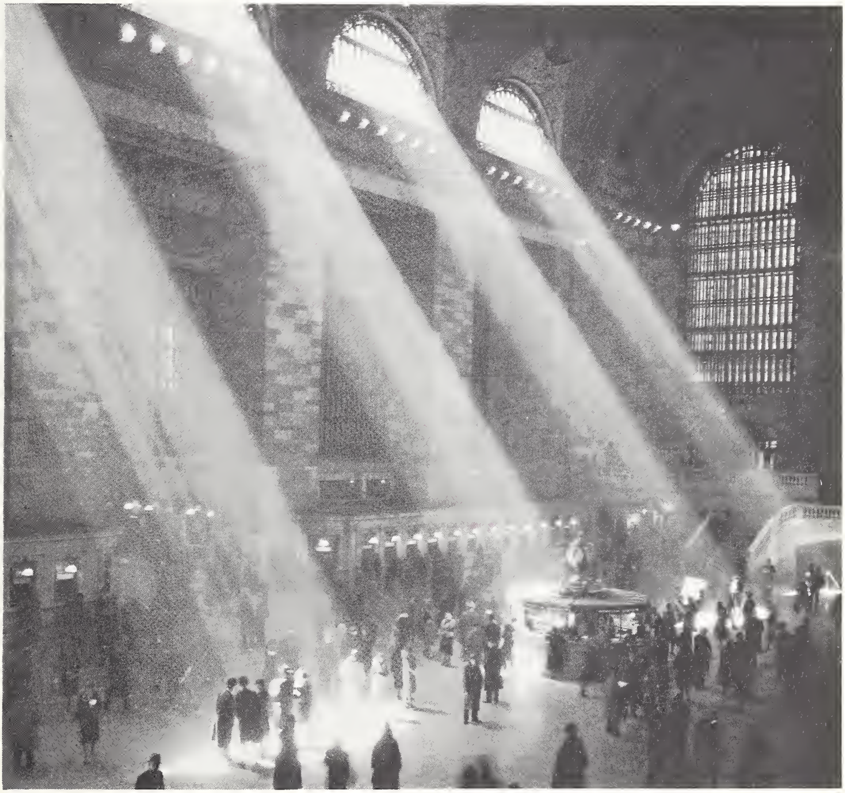


Fig. 21-1. The sun's rays coming through the windows of Grand Central Terminal in New York City show that light travels in straight lines. The rays are visible because the light is reflected from dust in the air.

Light travels through a vacuum, otherwise light from the sun would not reach us. It travels at the tremendous speed of 186,000 miles per second. At this speed it would take light only one-seventh of a second to travel around the earth.

Light travels in straight lines. How can we prove this? The shadow cast by an irregular-shaped piece of cardboard held in sunlight has the same shape as the cardboard. If you observe the shapes of shadows cast by buildings, clouds, telegraph poles, and other objects, you will see that their shapes can be explained only by the fact that light travels in straight lines.

Reflection of Light

When light strikes a flat opaque surface, its direction is changed, an effect known as *reflection*. The following experiment shows how light is reflected from a smooth surface.

Experiment

21-1. To reflect light from a mirror

Place a small mirror flat on a table in a darkened room. Direct the beam from a flashlight toward the mirror, as shown in Fig. 21-2, and place a large piece of white cardboard in the reflected beam. To narrow the beam, the face of the flashlight should be covered by a piece of black cardboard that has a hole about a quarter of an inch in diameter, placed between the center and the edge of the lens. A little chalk dust shaken into the beam, will help to make the light visible.

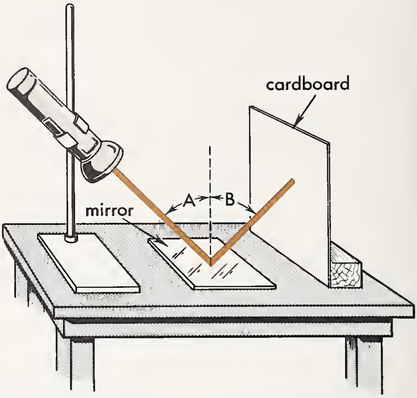


Fig. 21-2. Reflection of light from a mirror. The angle of reflection, B, equals the angle of incidence, A.

Follow the path of the light from the flashlight to the white cardboard and, with a protractor, measure the angles A and B shown in the figure. These are the angles between the beam of light and the perpendicular to the mirror. Angle A, the angle at which the light strikes the mirror, is called the *angle of incidence*; angle B, the angle at which the light is reflected from the mirror, is called the *angle of reflection*. How do these angles compare? Change angle A by

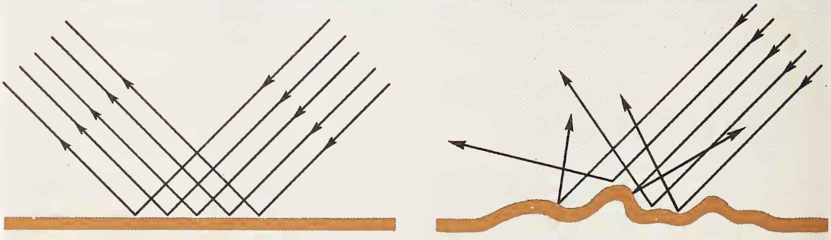


Fig. 21-3. Regular reflection (left) and diffuse reflection (right).

moving the flashlight and move the white cardboard until it is again in the path of reflected light. Again measure and compare angles A and B.

You will find that the angle at which a light beam is reflected from a mirror is always equal to the angle at which it strikes the mirror. In other words, ***when light is reflected from a smooth surface, the angle of reflection equals the angle of incidence.***

What is a mirror? A mirror is a very smooth surface that gives ***regular reflection***; that is, if parallel rays of light strike the surfaces, they continue parallel after they are reflected (Fig. 21-3). If light is reflected from a surface that is not perfectly smooth, it is scattered in all directions. This is called ***diffuse reflection***, and light reflected in this way is called diffuse light.

Some substances such as glass, water, and plastics reflect only a small amount of the light that falls on them, most of it passing through. Such objects are said to be ***transparent***. Other objects, such as rocks, walls of buildings, and countless other things around us, permit no light at all to pass through. They are called ***opaque***. Still other materials let light pass through them, but scatter most of the light as it passes through. Such materials are said to be ***translucent***. The glass on most light bulbs, for example, is translucent in order to produce soft shadows.

Location of the Image in a Plane Mirror

If we look into a mirror, we see an image of ourselves. How and where is this image formed? The position of the image in a plane mirror can be found by the following method.

Experiment

21-2. An image in a plane mirror

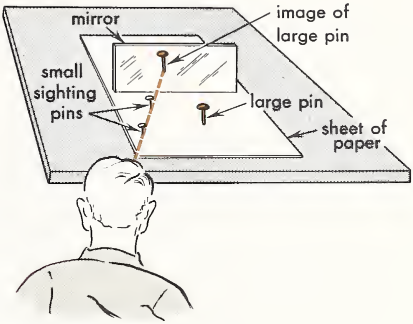


Fig. 21-4. Sighting the image of a large pin in a plane mirror.

Draw a long straight line in the middle of a large piece of paper. Then place the paper over a sheet of thick cardboard on a table and support a small mirror vertically so that its *back* edge lies along the line. Next stick a large pin vertically into the paper about 4 inches from the front surface of the mirror as shown in Fig. 21-4. Now, with one eye closed, locate the image of the pin by looking into the mirror along the table. Then stick 2 small pins into the paper as far apart as possible, as shown in Fig. 21-4. These pins must be *exactly* lined up with the image of the large pin. The image of the large pin lies along this line. Now repeat the process sighting along a different direction. The image of the large pin also lies along this line. Remove

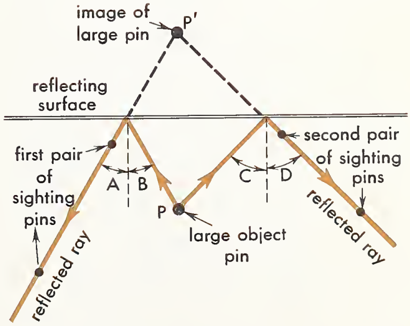


Fig. 21-5. Locating the image of a large pin in a plane mirror.

the pins and the mirror and, with a ruler, draw a diagram like that in Fig. 21-5, using the pinholes in the paper to determine the lines.

Since light from the large pin is reflected from the mirror according to the law of reflection, angle A equals angle B, and angle C equals angle D. Extend the lines of the two reflected rays behind the mirror. They intersect at a point P. This means that, to the eye, the two reflected rays *appear* to be coming from this point. This is so because we always judge the position of an object by assuming that light travels *in a straight path* from the object to the eye. Point P′ is therefore the position of the image, and the pin *appears* to be at this point. Careful measurements on the diagram show that ***this image of the pin is as far behind the mirror surface as the pin is in front of it.***

Mirror Images Are Reversed

Suppose we substitute an extended object (a figure of a boy) for a point object (the pin). Such an object and its corresponding image is shown in Fig. 21-6. Notice that in accordance with the law of reflection, each point on the image is exactly as far behind the mirror as the corresponding point on the object is in front of the mirror. Since the image of the boy faces a direction opposite to that of the object (the boy), his left hand and right hand are reversed in the image. ***All images formed by a plane mirror are reversed.*** That is why two things which are exactly the same but reversed, left to right, such as two symmetrical wings of a building are said to be "mirror images" of each other. Have you ever tried reading print by holding it up to a mirror? Print the words, TOT, MAT, and BUT on a piece of paper and try to read them in a mirror. Can you explain what you see?

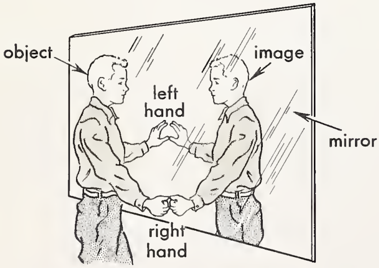


Fig. 21-6. Images in a plane mirror are reversed, left to right. Is the upper hand of the boy's image the left or right hand?

Fig. 21-7. Refraction of light by water. This painting shows Alhazen, famous eleventh century Arabian scholar, studying the bent appearance of a stick in water. This led him to dispute the ancient theory that visual rays emanate from the eye.

When the driver of an automobile looks at the road behind him in the rear vision mirror, everything he sees is reversed. The printing on signs is backward and the cars behind him appear to be driving on the wrong side of the road.

Refraction of Light

If a stick is partly immersed in a pail of water, it appears to be bent at the point where it enters the water. Why is this? This apparent bending of the stick is actually due to the bending of light; that is, light coming from the stick beneath the

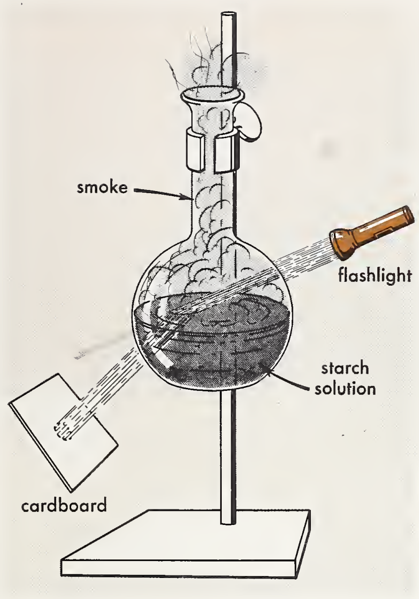


Fig. 21-8. Water bends a beam of light.

surface of the water is bent just as it leaves the water. The bending of light in this manner is called *refraction*. It can be shown in the following way:

Experiment

21-3. The refraction of light

Half fill a large round-bottom flask (one liter) with starch solution. Darken the room and direct the beam of a flashlight through the water as shown in Fig. 21-8. Find the emerging beam of light with a piece of white cardboard.

Imagine a line drawn perpendicular to the surface of the solution through the point at which the beam of light enters as shown in Fig. 21-8. Notice that, as the light goes from the air into the water, it is actually bent *toward the perpendicular*. If the light were going from the water into the air it would follow the same path but in the reverse direction; that is, as it left the water it would be bent *away from the perpendicular*.

These facts can be summarized in the *law of refraction*, which states: ***Whenever light goes from a less dense to a more dense substance, it is bent toward the perpendicular; conversely, whenever light goes from a more dense to a less dense substance, it is bent away from the perpendicular.***

How can we explain the apparent bending of a stick partly immersed in water? Light from the submerged part of the stick is bent away from the perpendicular as it emerges from the water. As a result, the light comes to our eye in such a direction that each of the submerged parts of the stick appears to be a little higher than it really is. This is shown by Fig. 21-9.

When the Indians shot fish underwater with bows and arrows, they were confronted with this bending effect when aiming at their targets. They found by experience that to hit the fish they had to aim a little below where it appeared to be.

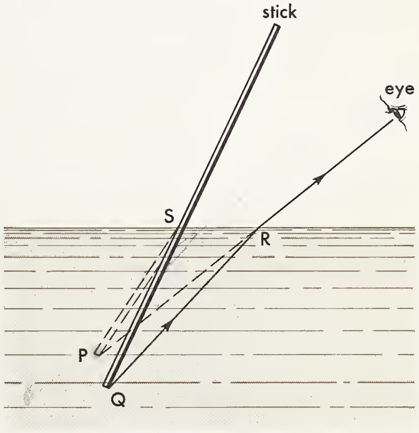


Fig. 21-9. A stick appears bent in water because light from point Q on the stick is bent as it leaves the water and the eye sees this point on the stick at P instead of at Q. All other parts of the stick that are submerged appear at different positions so that the image of the submerged stick appears along PS.

Another interesting demonstration of refraction can be performed with a small bowl, a coin, and some water.

Experiment

21-4. Seeing over the edge of a dish by refraction

Place a coin on the bottom of a shallow dish or bowl and sight over the edge of the bowl, lowering your head until the coin just disappears from view behind the edge of the dish. Without moving your head, slowly pour water into the dish. As the surface of the water rises the coin will come back into view. The path of the light and the position of the image of the coin is shown in Fig. 21-10.

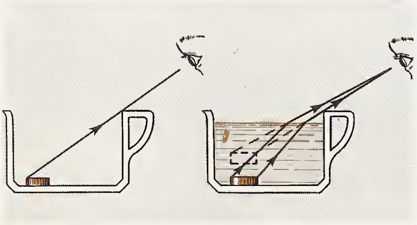


Fig. 21-10. Seeing over the edge of a dish by refraction.

Lenses

A *lens* is a curved piece of glass and is used to bend light rays so that they can be put to practical use. There are two types of lenses–convex and concave–that are used in optical instruments (see Fig. 21-12). A *convex* lens is thicker in the middle than at the edges; a *concave* lens is thicker at the edges than in the middle.

A convex lens can be used to concentrate both light and heat at a point. Before the invention of the Bunsen burner, the heat of the sun was concentrated in this way to provide heat for chemical reactions. The following experiment, for example, suggests how potassium chlorate might be decomposed in this way to yield oxygen.

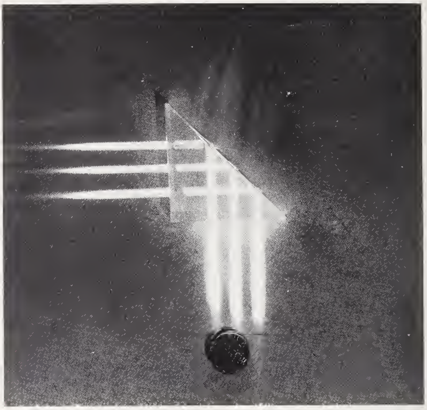


Fig. 21-11. The back of this prism reflects rather than refracts light. Can you explain why?

Experiment

21-5. To use a convex lens to concentrate the rays of the sun

Hold a large convex lens between a piece of white cardboard and the sun. Move the

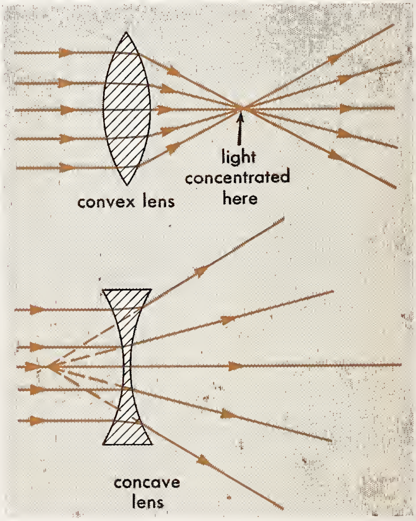


Fig. 21-12. Refraction of light by a convex (top) and concave (bottom) lens.

lens back and forth until a small bright spot appears on the cardboard. The bright spot is an image of the sun, whose light striking the lens is concentrated on this spot.

The path of the sun's rays through the lens is shown in Fig. 21-12. Notice how the rays are bent as they pass through different parts of the lens. This type of bending may be used to form images on a movie screen or images in telescopes and microscopes.

Things to Remember

Light travels at a speed of ***186,000 miles per second.***

Light waves travel in ***straight lines.***

When light is reflected from a smooth surface, the ***angle of reflection is equal to the angle of incidence.***

The ***image*** in a plane mirror is always as far behind the mirror as the object is in front of it.

Images in a plane mirror are ***reversed.***

Light is always bent ***toward*** the perpendicular to the surface when it passes from a less dense to a more dense substance, and ***away*** from the perpendicular when it passes from a more dense to a less dense substance.

Convex lenses are used to concentrate light and produce images.

Questions

Part A

1. What is the speed of light?
2. What is diffuse light?
3. Give an example of: [**a**] a transparent substance, [**b**] an opaque substance, [**c**] a translucent substance.
4. What is meant by the reflection of light?
8. Where is the image formed in a plane mirror?
5. Name three optical devices that contain lenses.

Part B

6. Describe a method of concentrating light at a point.
7. Describe an experiment that shows how light is refracted.

Things to Do

To Make a Periscope

A simple periscope is easy to construct. It can be used for looking over fences and to see over people's heads in a crowd.

Make a long rectangular wooden box out of thin wood. It should be about 2 or 3 feet long (the shorter the tube, the greater the field of vision) and about 4 or 5 inches square. Cut 2 square holes close to the ends on opposite sides of the box, and glue two mirrors into these holes at a 45-degree angle, as shown in Fig. 21-13. You can use cheap mirrors and have them cut to size at a hardware store. The whole apparatus can be painted black, both inside and out, and a handle can be attached to each side near the base.

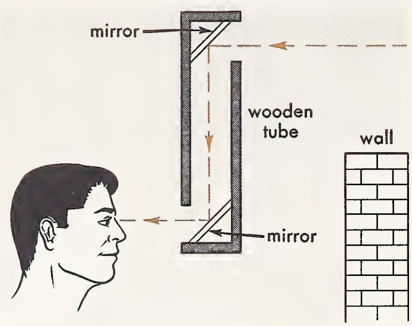


Fig. 21-13. A simple periscope.

22

Optical Instruments

The principles of reflection and refraction apply to many optical instruments. In this chapter we shall study some of these instruments–the camera, the human eye, the telescope, and, in the next chapter, the spectroscope.

A Simple Camera

You probably know already that a simple, inexpensive camera consists of a light-tight box with a convex lens mounted at one end and a photographic film at the other (see Fig. 22-1). When a picture is being taken, a shutter, mounted in front of the lens, is opened for an instant to admit light from the objects being photographed. The light passes through a lens and is refracted, forming an image on a film coated with a chemical that is sensitive to light. When properly developed, the film holds a permanent impression of the image, thereby forming a negative.

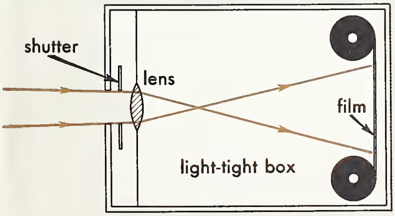


Fig. 22-1. The path of the light rays in a simple camera.

All cameras, regardless of their price, operate in this manner but, in order to get pictures under poor conditions, various devices are added and better lenses are used.

Fig. 22-2. A large aerial camera such as is used to photograph large areas of the earth's surface from high altitude. The photographs can then be used in preparing maps.

Many people find it interesting to carry through the whole photographic process by developing films and printing pictures themselves. Although the process is fairly involved, the principles are easily understood.

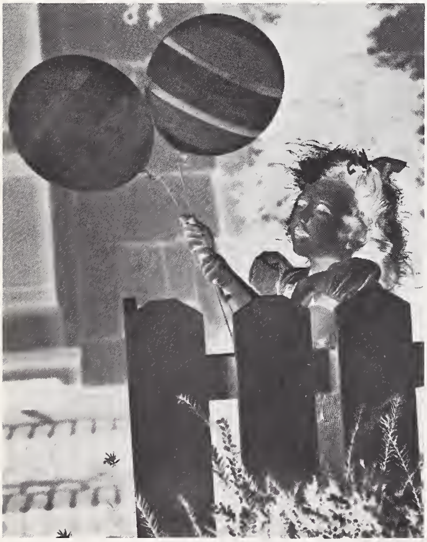
A film usually consists of a plastic strip coated with a layer of gelatin. Small light-sensitive crystals of a substance such as silver bromide are scattered throughout the gelatin. When light hits the silver bromide, a change occurs in the crystal structure, so that the silver bromide can form metallic silver more easily after exposure than before. The metallic silver is black, thereby showing the light parts of the photographed scene as dark. The dark parts of the scene do not supply much light and so have little effect on the silver bromide.

After a picture is taken the film is developed; that is, it is placed in a solution of a developer and the exposed parts are reduced to silver. The unexposed silver bromide is then dissolved by hypo (sodium thiosulphate), so that it will not turn black. When the film has been washed and dried, it is a ***negative***, so called because it shows the picture in reverse, as in Fig. 22-3A.

A ***print***, or finished picture, is made by placing the negative in contact with a piece of photographic paper coated with a light-sensitive emulsion similar to that on film, and then exposing the paper to light through the negative. This paper is then developed, fixed in hypo, washed, and dried. If all steps are performed correctly, the print will be a true picture, called a ***positive***, of the original scene to which the film was exposed.

The Eye

The human eye is the most sensitive of all optical instruments. In some respects it is like a camera. Can you name the similarities between the eye and the camera? Like the camera, the eye is a light-tight compartment, but it is spherical in shape. Also like a camera, it has a lens in front and a sensitive "film" at the back on which



22-3A. A photographic negative.

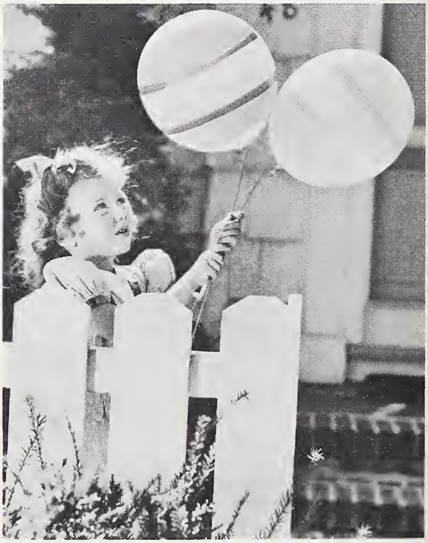


Fig. 22-3B. A positive photographic print made from the negative in A.

images are focused. The sensitive film of the eye is called the *retina*. But here the similarity ends.

The film of a camera is shielded from light until the instant the exposure is made, after which the picture must be developed. Moreover, the film can take only one exposure, otherwise it is spoiled. The retina of the eye, on the other hand, receives impressions continuously, and these impression are "developed" instantly by the brain. In this respect the eye is more like a television camera than a photographic camera.

The Retina

The retina is a delicate layer about 1/50 of an inch thick. It consists of the cells of nerve endings that are sensitive to light, and it is connected to the brain by "transmission lines" which make up the *optic nerve*.

The cells at the center of the retina are cone-shaped, and are called *cones*; those along the edges are rod-shaped, and are called *rods*. The cones and rods serve different purposes. With the cones we see details and distinguish colors during the daytime. But the cones are not very sensitive and do not respond to the low illumination encountered at night; in fact, at night the center of the eye is practically blind. The rods, on the other hand, do not see detail sharply nor do they respond to different colors; they are sensitive to only light and dark like a black-and-white photographic film. At night they respond to the faintest light, so that, if the atmosphere is clear, one can see a candle flame as far as 14 miles away. Thus we really have two kinds of vision–day and night vision.

How sensitive are our eyes? With how little light can we see? We can easily see objects by moonlight, but our vision is not keen; grass and leaves of trees, for example, appear gray, not green. This is because we see by rods which are not sensitive to color. Full moonlight is only 1/500,000 as bright as sunlight. Starlight is even dimmer–it may be only one-thousandth as bright as moonlight–yet we can see by it, although the outlines of objects are blurred.

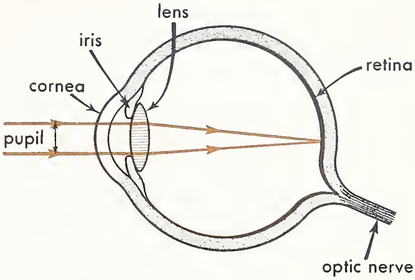


Fig. 22-4. The lens of the eye acts like the lens of a camera, the retina acts like the film in a camera.

As we step from a well-lighted room into the darkness of night we are at once aware of the different responses of rods and cones. The cones no longer act, and the rods require some minutes to regain their sensitivity, so that we are temporarily blind.

Most animals have good night vision, but some have keener night vision than others –owls and mice, for example, have night vision; chickens, on the other hand, like most birds, have poor night vision and go to roost when it gets dark.

The Iris

The retina can respond to only a small variation in light intensity; too strong a light can injure it. How can the eye take care of such a wide range of light intensity as the difference between that of sunlight and moonlight? This is accomplished automatically by the joint action of the eye, nervous system, and brain by means of a feedback system. When the light intensity on the retina is too great, the brain automatically relieves the strain by sending nerve impulses (feedback) to the muscles controlling the *iris* in the eye. The iris, operating like the diaphragm in a camera, partially closes the opening in front of the eye lens so that less light gets through to the retina.

When you step outdoors from a brightly lighted house into the dark, the process is reversed–the iris opens wide to allow enough light to enter the eye so that the rods will respond to the low level of illumination. (It is the iris, surrounding the pupil of the eye, that is blue, brown, gray, or hazel, giving the eye its color.) It is actually possible to observe the opening and closing of the iris by standing in front of a mirror within easy reach of a light switch. Stand in dim light and look at the pupils of your eyes. Then snap on the light, and you will see the iris close down the size of the pupils as the sudden increase in illumination sets the automatic feedback reaction into operation. Have you ever noticed how large the pupils of a cat's eyes are in dim light and how small they are in bright sunlight?

When the illumination level is high and the pupil is small, so that light only comes through the center of the eye lens, the image formed on the retina is clear and sharp. When the illumination is low, the image on the retina is the same size, but it is less clear due to distortion of the light rays coming through the edges of the spherical lens when the iris is wide open. Camera lenses also suffer from this kind of distortion, and the sharpest pictures are obtained from a camera in bright light when the "iris" in a camera is nearly closed, or "stopped way down" but still admitting enough light to properly expose the film. This effect also explains why strong illumination is best for fine, detailed work with the eyes, such as fine needle work or watch-making. With strong illumination, the iris closes the pupil to a small opening, distortion is reduced, and the image on the retina shows fine detail clearly.

Eye Defects

The eye is a complex, precision mechanism. It is not surprising, therefore, that all its parts do not always function perfectly. Few of us are entirely free from eye defects, such as nearsightedness, farsightedness, and astigmatism. To correct such defects we wear glasses.

In normal vision the muscles of the eye either flatten or round out the eye lens to change the distance at which light converges to form an image, so that a sharp image of either a distant or a close object is formed on the retina. This change in the curvature of the lens for changing object distances is called *accommodation.* In *nearsighted* persons, the eyeball is so long that the image of a distant object is formed in front of the retina and is therefore blurred. Objects close to the eye can be seen clearly, since the image of nearby objects is formed well behind the lens. Nearsightedness can be corrected by a concave, or diverging, lens placed directly in front of the eye as shown in Fig. 22-5. ***Farsighted*** persons cannot see nearby objects clearly because the eyeball is so short that the image forms behind the retina, as shown in Fig. 22-6. This condition can be corrected with a convex lens. If you wear

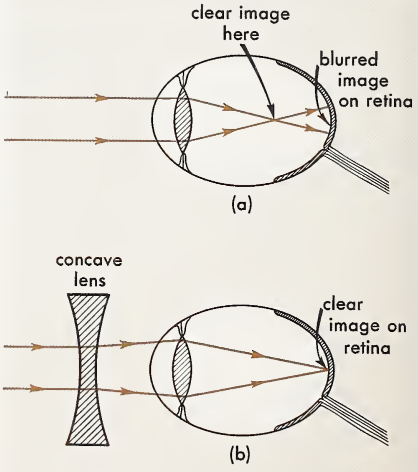


Fig. 22-5. The eyeball in a nearsighted eye (a) is too long and gives a blurred image of distant objects on the retina. Glasses with concave lenses (b) will correct nearsightedness.

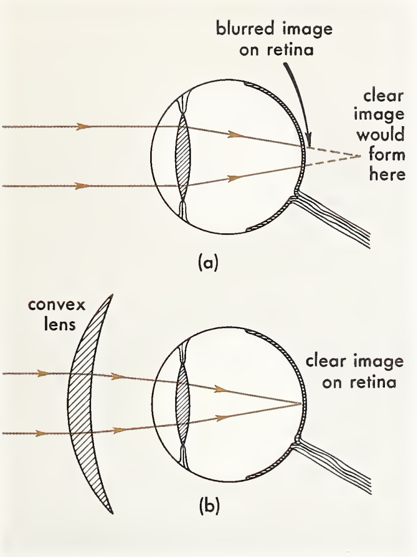


Fig. 22-6. The eyeball in a farsighted eye (a) is too short and gives a blurred image of nearby objects on the retina. Glasses with convex lenses (b) will correct farsightedness.

glasses, are they concave or convex? Are you nearsighted or farsighted?

In some eyes, the *cornea*, which is in front of the lens, is not curved equally all over its surface. This causes an image to be formed that is sharper in one direction than in others, a defect called ***astigmatism***. Astigmatism is the most common eye defect, although in many cases it is not serious enough to require correction. However, it too can be corrected by glasses. You can test your eyes for astigmatism by using Fig. 22-7. To make this test, slowly turn the book around while looking at the diagram. If one set of lines first looks sharper than the others, and then, with further turning, becomes blurred while the other lines become sharp, you have astigmatism.

Telescopes

A telescope is an instrument for viewing distant objects (the word *telescope* means to see distant objects). There are two kinds of telescopes—astronomical and terrestrial. In an astronomical telescope everything is seen upside down. Since such telescopes are used mainly for photographing heavenly bodies, an upside down image is not important. A terrestrial telescope, on the other hand, must give an erect image, otherwise ships and other objects would be seen upside down. To make the image erect, a terrestrial telescope has an extra lens between the objective and the eyepiece. This extra lens absorbs some light and introduces some distortion in the image, but the advantage of seeing things right side up on the surface of the earth outweighs these defects.

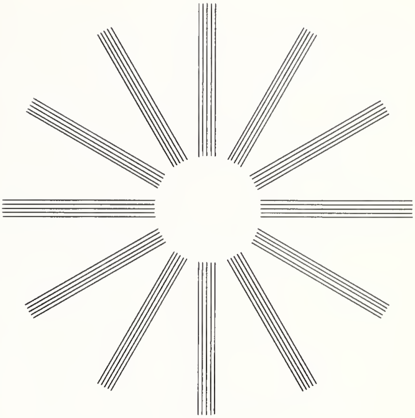


Fig. 22-7. A chart to test for astigmatism.

Refracting Astronomical Telescopes

An astronomical telescope which uses a lens to converge light to form an image is a ***refracting telescope***. It is shown in Fig. 22-8. Since the object is always at a great distance from the lens, the light from the object gives a small upside down image. This image is then viewed by a smaller eyepiece lens that forms an enlarged image which is viewed by the eye. This image is, of course, still much smaller than the original object. Nonetheless, when using a

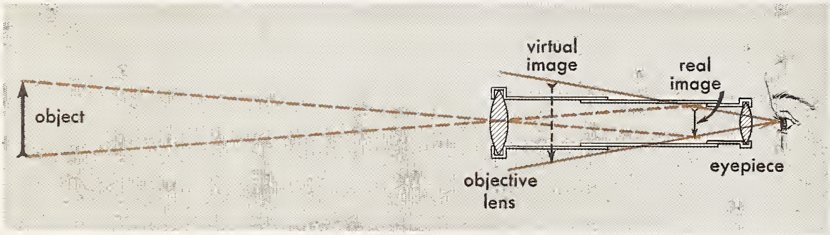


Fig. 22-8. A diagram of a simple refracting astronomical telescope.

telescope, the image on the retina is much larger than it would be without the aid of the telescope.

Reflecting Astronomical Telescopes

As the name suggests, a reflecting telescope reflects rather than refracts light. In this kind of telescope the light-collecting lens is replaced by a concave mirror. The first reflecting telescope was built by Sir Isaac Newton in the seventeenth century. It was only 6 inches long and magnified objects only 40 times. In principle, modern reflecting telescopes are the same as Newton's, but in size they are giants by comparison.

What is the advantage of a reflecting telescope? Since a lens must be accurately ground on *both* faces, it is difficult to make large accurate lenses for refracting telescopes. A mirror, however, needs to be ground accurately on one side only. For this reason the largest modern astronomical telescopes are of the reflecting type. The ground concave glass face must be silvered to form a mirror. The telescope on Mount Palomar in California is the most familiar example of a reflecting telescope and is

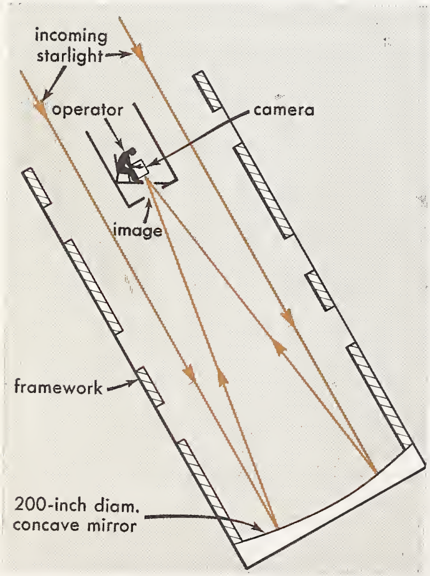


Fig. 22-9. A simplified diagram of the path of light rays in the reflecting telescope on Mount Palomar in California.

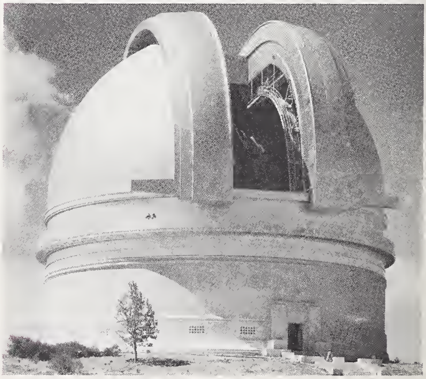


Fig. 22-10. The Mount Palomar observatory, which houses the largest (200-inch) reflecting telescope in the world. Its size can be gauged by looking at the two people on the balcony (above the tree in the foreground).

discussed later in the chapter. Whether telescopes are refracting or reflecting, the light-collecting lenses are of large diameter. Why is this? The larger the diameter, the greater is the amount of light concentrated at the image, so that the images of faint and distant objects are bright enough to be seen or photographed.

Taking Photographs with Astronomical Telescopes

Large astronomical telescopes, whether refracting or reflecting, are rarely used for direct observation by the eye; they are used as cameras. There are several reasons for this. Observations made by the eye are limited to one observer, whereas a photographic plate makes pictures available to all astronomers. Then again, the camera records many distant objects that the eye cannot see. The reason for this is fairly obvious. Suppose you are looking at a faint star through a telescope. No matter how long you look at it, the star does not get any brighter. This is not true of a camera. If light strikes a photographic plate for a few seconds, a certain amount of detail is recorded; and if the length of the exposure is increased, fainter detail is also recorded. That is, if the exposure is long enough, enough light from a very faint object will fall on the photographic plate to expose it and be recorded.

The Site of the Telescopes

You probably have noticed that large astronomical telescopes are usually located on high plateaus or mountains, far from cities. Do you know why? Telescopes should have a clear view of the sky in all directions. The astronomer needs a very transparent atmosphere which is found only at high altitudes, and away from the smoke and dust of cities. At high altitudes,

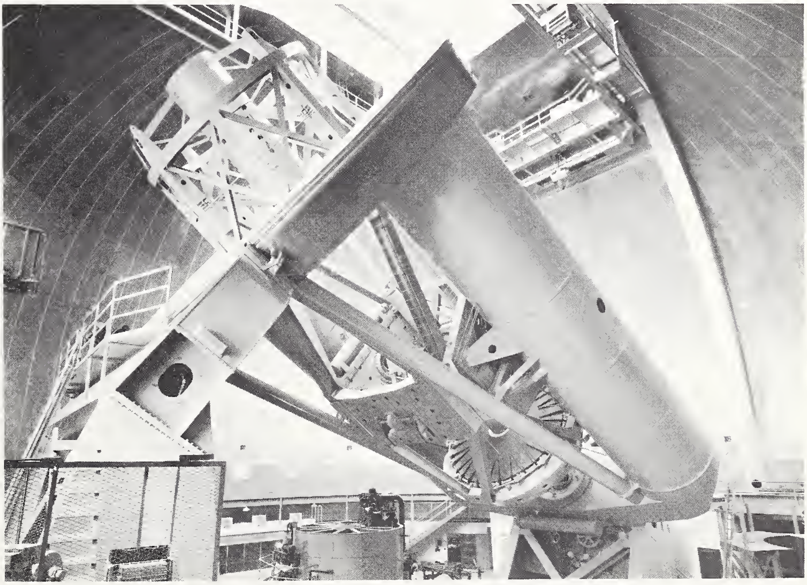


Fig. 22-11. The Mount Palomar telescope. The 200-inch mirror (lower right-hand corner) is covered to protect its delicate surface. The eyepiece, or camera, is located in the cylindrical tube in the upper left-hand corner.

too, there is little convection. Convection currents in the air refract starlight in an irregular way, making the stars twinkle and giving blurred images on a photographic plate. The lights of a large city give so much diffuse light in the sky that faint stars cannot be seen.

The Palomar Telescope

The Mt. Palomar telescope, the largest in the world, was constructed in southern California in 1948. It is located on a broad plateau 5600 feet above sea level and is a gigantic steel and glass structure, weighing almost 500 tons. It is housed in a steel-and-concrete dome, 70 feet high.

The mirror in this telescope is a 15-ton disk of glass which was ground and polished to exact shape and then coated with a thin film of aluminum to reflect the light. It is 200 inches (nearly 17 feet) in diameter, and it concentrates the light as shown in Fig. 22-9. This arrangement does not need a tube, but simply a supporting framework. A cylindrical chamber about 6 feet in diameter is suspended near the image. Here the astronomer sits with an eyepiece through which he checks the image to be photographed by the camera. The operator reduces the amount of light falling on the mirror only very slightly and does not distort the image. The camera has no lens of its own. It is simply adjusted so that the image formed by the large mirror is focused on a photographic plate. The pictures taken in this way can then be enlarged so that detail can be carefully examined.

The large-diameter mirror of the Palomar telescope collects a great amount of light. As stated earlier, the unaided eye in darkness can see a candle flame 14 miles away. Viewed through the 200-inch telescope, the same candle flame would be visible 14,000 miles away; and with a photographic plate, the telescope could "see" the candle flame 40,000 miles away! The Palomar telescope, with a mirror the diameter of which is about 1000 times that of the pupil of the human eye, intercepts as much light as one million human eyes. It took twenty years to build, at a cost of more than ten million dollars. What is the purpose of this colossal instrument?

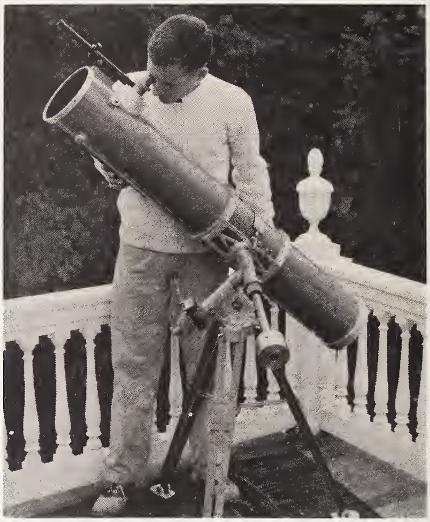


Fig. 22-12. A 6-inch reflecting telescope. The whole telescope, including the grinding of the 6-inch concave mirror, was constructed by an amateur astronomer.

For thousands of years man has been trying to understand the universe he lives in. At one time he believed the earth was the center of the solar system, and that the universe was composed of only the 5000 or so stars visible to the naked eye. Astronomical instruments have revealed many facts about the universe. But there is still much that man wants to know. Is the universe expanding? Is the earth the only place where intelligent life exists? Or are there other solar systems, among the millions of suns, with planets that can support life? Astronomers believe that Palomar will solve some of the mysteries of the universe. Some of these fundamental problems of astronomy will be discussed in a later chapter.

Things to Remember

A simple *camera* consists of a shutter, a lens, and a light-sensitive film mounted in a light-tight box.

The most important parts of the *human eye* are a lens, a light-sensitive surface called the retina, and an iris that controls the amount of light entering the eye.

The *retina* is composed of cells called rods and cones.

The *cones* register detail and color, but are not very sensitive.

The *rods* do not see detail or color, but are very sensitive and are used at night.

A *refracting astronomical telescope* contains a large *light-collecting* lens and a smaller *eyepiece.*

A *reflecting astronomical telescope* contains a large *light-collecting* mirror and a small eyepiece.

Most astronomical telescopes are used *as cameras* to increase their sensitivity, and to give a permanent record.

The *Mount Palomar* telescope has a 200-inch concave mirror.

Questions

Part A

1. Name three optical devices that contain lenses.
2. What is the purpose of the shutter in a camera?
3. How does a camera [**a**] resemble the eye, [**b**] differ from the eye?
4. What is [**a**] nearsightedness, [**b**] farsightedness? How can each be corrected?
5. What is the purpose of the light-collecting lens in a refracting telescope?
6. Why should astronomical telescopes be located far from cities?
7. What is the difference between an astronomical telescope and a terrestrial telescope?

Part B

8. What is astigmatism and how can it be corrected?
9. Draw a diagram of an astronomical telescope, showing where images are formed.
10. What is the advantage of using an astronomical telescope as a camera?
11. Draw a diagram of [**a**] a simple camera, [**b**] the eye.
12. What is the function of [**a**] the rods and cones, [**b**] the iris in the human eye?
13. Is it possible to photograph the image formed by a plane mirror? Give reasons.
14. A very faint star is most easily seen if you do not look straight at it but view it out of the "corner" of your eye. How do you explain this?

Things to Do

How to make a simple telescope

You can make a simple telescope by mounting two convex lenses in lens holders on a meter stick. The focal length of the light-collecting lens should be as much greater than that of the eyepiece as possible. Move the eyepiece back and forth, until a clear image of a distant object is seen when looking through both lenses.

You can measure the magnifying power of your telescope by looking at a line of distant electric light poles or other evenly spaced objects with both eyes open, so that the magnified image (as seen by the eye looking through the telescope) and the image seen by the unaided eye overlap. Now compare the spacing of the two images of the light poles. The ratio of the spacing of the poles seen through the telescope to the spacing seen without the telescope is the magnifying power of the telescope.

23

What Is Color?

When we see the colors of a sunset or of flowers, or of an outcrop of pink granite or red sandstone, or of an apple tree in spring, or of maple leaves in autumn, we realize that much of the beauty of nature is due to color. It would be a drab world indeed without color.

Birds can see colors, and some insects, such as bees and butterflies, can also see them. But there is reason to believe that most other animals like dogs and horses, for example, see only black and white. The retina of a horse's eye is somewhat like ordinary photographic film that is sensitive only to light and dark. The retina of the human eye is more complex; it can be compared to color film in that it contains cells (cones) sensitive to different colors. But some people are unable to distinguish certain colors because of a deficiency of cones sensitive to certain colors. They are said to be color-blind. The commonest form of color blindness is the inability to distinguish red from green. Since these colors are used for traffic lights, all engineers on railroads are carefully tested for color blindness. On highways, traffic lights often have small amounts of colors besides red or green so that they can be properly distinguished by color-blind people. Strangely enough, color blindness is far more common in men than in women.

Newton's Investigation of Color

The nature of color was first investigated by Sir Isaac Newton in the seventeenth century. Newton allowed a beam of sunlight to pass through a narrow slit in the window shade of a darkened room so that it gave a patch of light on the opposite wall. He then held a glass prism in the

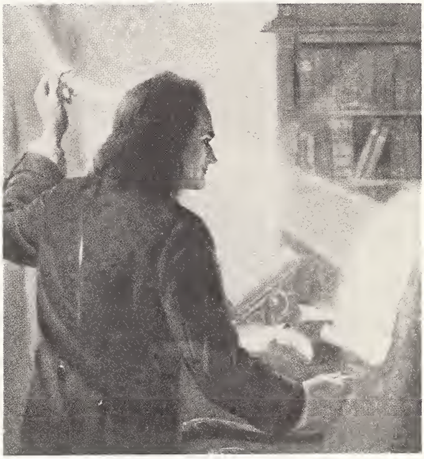


Fig. 23-1. An artist's conception of Newton's experiment in which Newton used a prism to split up white light into its separate colors.

beam of light. The white patch disappeared and, in its place, a long band of color appeared on the wall above the patch. The band was made up of various colors: red at the bottom, then orange, yellow, green, blue and, finally, violet at the top. Such a band of colors is a ***spectrum***.

Newton's classic experiment is very important. Let us make a spectrum for ourselves.

Experiment

23-1. Formation of a spectrum

Do this experiment in a dark room. Cover the lens of a flashlight with a piece of black paper. A slit should be cut into the paper so that only a narrow beam of light passes through. Place a glass prism on a stand near a white cardboard screen and direct the beam of light toward the prism. Rotate the prism on its vertical axis until a band of colors appears on the screen, as shown in Fig 23-2.

How does a glass prism form a spectrum? White light is really a mixture of many colors. The different colors are bent, or refracted, by different amounts as they pass through a glass prism, violet being refracted the most and red the least. It is the difference in the amount of bending that causes the colors to separate.

Glass prisms on "crystal" chandeliers break up white light into its spectrum colors. In this way, color brilliance is added to a room. But many other transparent substances besides glass will separate white light into its constituents. A diamond, for example, bends the light rays even more than glass so that it sparkles with brilliant reds, greens, and blues. The most familiar example, however, of the breaking up of light is the rainbow. This is nature's spectrum. It is formed when sunlight is separated into its colors by drops of water.

The Rainbow

When sunlight enters a raindrop, the white light is refracted as it goes from air to water. It is then reflected inside the drop, and refracted again as it emerges from the drop. The violet light is refracted more than the red light; when the light emerges, therefore, the colors of the spectrum are separated just as in a prism (see Fig. 23-3).

Have you noticed that to see a rainbow you must stand with your back to the sun?

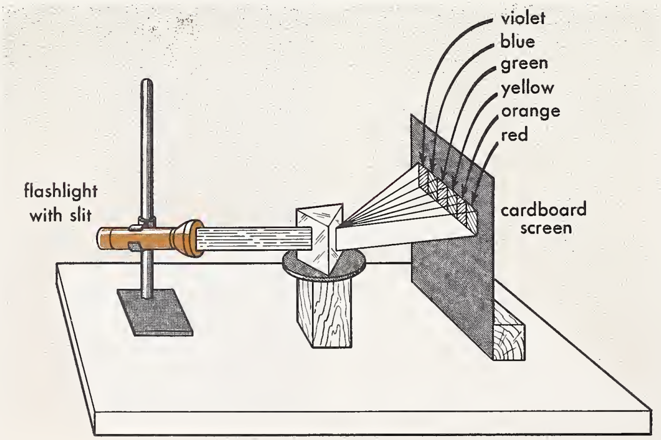


Fig. 23-2. Splitting up white light by a prism.

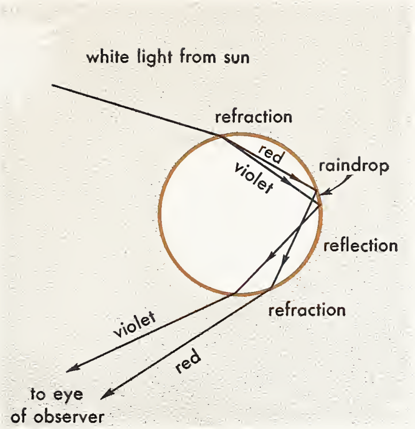


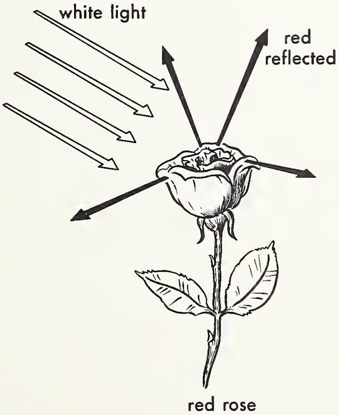
Fig. 23-3. How a raindrop splits white light into its component colors to form a rainbow.

Do you know why? A rainbow appears as a semicircular arc of light in the direction opposite to the sun. It is only the raindrops along this particular arc that send back the spectrum colors to your eye. The raindrops outside the arc also split up the sunlight, but the colored rays that emerge do not enter your eye. A person standing in a different place will see the spectrum produced by some of these other drops of water. In other words, each person sees his own particular rainbow. A rainbow can also be seen when you stand near a fountain or a garden spray with your back to the sun. How can you explain this?

Sometimes a faint circular "rainbow" can be seen around the moon at night. This has often been taken as a weather sign indicating approaching rain. No single sign can foretell the weather with certainty, but this particular sign has a good basis in fact. The "rainbow," or halo, as it is more properly called, is caused by the refraction of the moon's light by tiny ice crystals of a particular shape that occur in thin cirrus clouds several miles above the earth. These clouds often precede a warm front, and a warm front usually brings rain.

Color of Objects

The spectrum colors do not include all the colors you are familiar with; neither brown nor purple, for instance, is a spectrum color. The spectrum bands are called *pure* colors because they cannot be further separated. Only rarely do we find pure colors in nature; the colors in nature are usually



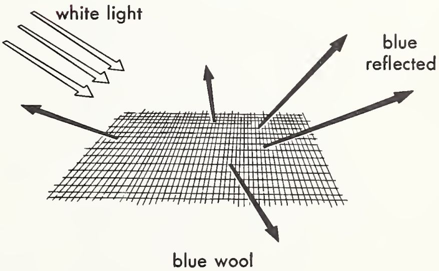


Fig. 23-4. Red objects absorb all colors but red, which they reflect. Blue objects absorb all colors but blue.

mixtures, like purple, for example, which is a mixture of red and blue.

This brings us to the question: What causes the color of objects? Why is grass green and blood red? Strangely enough, an object is colored because it removes, or absorbs, something from white light; it absorbs some colors and reflects others. The colors that are absorbed are "lost" in the form of heat, and the colors we see are only those that are reflected. For instance, if sunlight falls on a red rose, the blue and green are absorbed; whereas the red, orange, and a little yellow are reflected. The rose therefore appears red. The absorption and reflection of color by a red rose is shown in Fig. 23-4. On the other hand, a blue iris absorbs the colors at the red end of the spectrum and reflects only those at the blue end. The iris therefore looks blue.

It follows from this explanation that a rose can appear red only if there are red rays in the light that illuminates it. In other words, ***the color of an object depends on the nature of the substance itself and also upon the light that falls on it***. Let us illustrate this point in the following experiment.

Experiment

23-2. The color of objects illuminated by light of different colors

In a darkened room set up the apparatus used in Experiment 23-1, and hold a piece of red yarn in the beam coming from the prism. Hold the yarn so that it is illuminated only by blue and violet light. What color does it appear to be? Now examine a piece of blue yarn in the red part of the spectrum. In both cases the objects appear black. The red wool appears black, because in the blue light that illuminates it there are no red rays which the wool can reflect to the eye, and when no light falls on the retina, the brain gives us the sensation of "color" that we call black. Why does the blue wool appear black in red light? The absorption of blue light by red wool is shown in Fig. 23-4. Now examine the red wool in green and in yellow light and try to explain the color of the wool.

Next examine the red and blue yarns in the light of a sodium flame (see Experiment 23-3). This flame gives only yellow light. What is the color of each piece of yarn? How do you explain this color? Notice also the cadaverous appearance of the hands and face near the flame. How can you explain this?

Many dyes reflect more than one color. If, for example, a red tie with yellow stripes is viewed under sodium light, the red part will appear dark yellow, not black as one might expect. Try this with the apparatus used in Experiment 20-3. This is because the red dye reflects some orange and yellow as well as red. Examine a brightly colored tie in the sodium light. Can you explain the result?

It should now be plain why colors do not appear to be quite the same in artificial light as in sunlight. Two colors that match under artificial light may not match in daylight. A blue color, for instance, looks darker in artificial light than in daylight because there is less blue in artificial light. Again, we find that a red color appears more intensely red in artificial light than in daylight. Can you explain this?

A yellow filter (a piece of glass that is transparent to all but blue light) is often used on a camera to bring out or emphasize clouds in black-and-white landscape photographs. All colors are reflected by white clouds, and therefore they appear white in the photograph. But the strong blue light from the sky will also show up as white on a black-and-white photograph, and there will be little contrast between clouds and sky unless a filter is used to cut out the blue light of the sky. Thus, in a photograph taken using a yellow filter, clouds will stand out sharply against an almost black background of sky.

The Color of the Sky

If the earth had no atmosphere, the sky would be jet-black in the middle of the day.

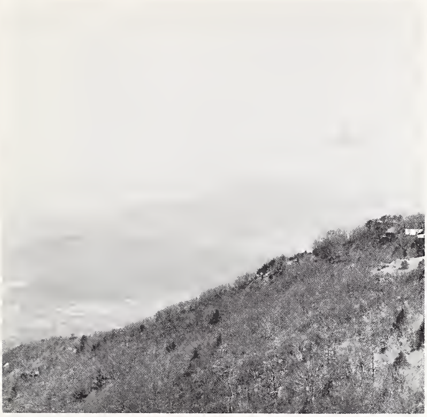


Fig. 23-5A. This photograph was taken without a color filter. Notice that the background is nearly obscured by haze and the sky appears uniformly gray with no visible clouds.

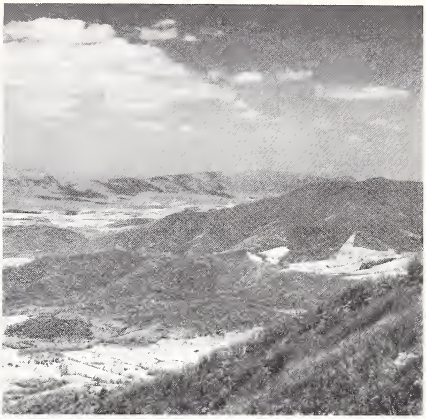


Fig. 23-5B. The same scene as Fig 23-5A, photographed with a yellow filter in front of the camera lens. Notice how the use of this filter penetrates the haze and brings out the contrast of white clouds and dark (blue) sky.

The sun would appear as a dazzlingly brilliant white orb, and the stars would be easily visible as bright points of light in the black sky. Actually, the sky is so bright that it obscures all but the brightest planets and the moon. Then why is the sky blue? The blue light of the sky is sunlight that has been scattered or reflected in all directions by bits of dust and gas molecules in the atmosphere. In whatever upward direction we look, scattered blue light enters our eyes. The colors in the blue end of the spectrum are scattered more than green, yellow, and red light, which are little affected. Since the direct sunlight is lacking in blue when it reaches our eyes, the sun appears slightly yellowish rather than pure white.

On some days the sky appears less blue than on others. Sometimes, even when the sun is shining brightly, the sky is almost pure white rather than blue. This is due to a layer of thin cirrus high up in the atmosphere through which much of the sunlight passes nearly unaffected. The water droplets in these clouds, however, are so much larger than air molecules that they scatter light from the red end of the spectrum as well as the blue end and we have all colors scattered, giving a white appearance to the sky.

Color of Sunsets

Nature displays her most gorgeous coloring in sunsets, particularly in the tropics. What causes the color of sunsets? When the sun is setting, light that comes directly to the eye travels through much more of the earth's atmosphere than when the sun is directly overhead. As a result, a great deal of light at the blue end of the spectrum is scattered, and the sun is dim enough to be viewed directly. The remaining light that comes directly to the eye is a beautiful red or yellow, depending on the amount and the type of dust in the air which causes the scattering.

All sorts of color combinations can result from scattering. A few clouds near the horizon will reflect the strongly colored sunset light and add to the beauty of the sunset. Some of the most beautiful sunsets are observed in the vicinity of forest fires,

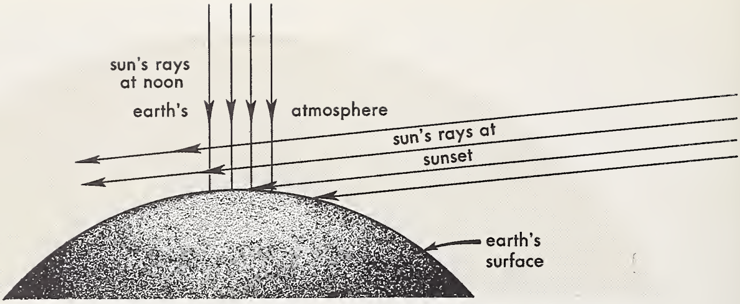


Fig. 23-6. The sun's rays travel through more of the atmosphere at sunset than at noon.

which fill the atmosphere with tiny smoke particles that cause a large amount of scattering. When the volcano Krakatoa, between Java and Sumatra, exploded in 1883, it hurled great quantities of volcanic dust into the upper air. Winds carried the dust to all parts of the world. Though the dust was so fine as to be completely invisible, it provided the whole world with exquisite sunsets for several years.

Color and Safety

Have you noticed that most highway traffic signs warning the motorist that he is approaching a crossroad, curve, stop street, or other danger point have black letters on a yellow background? The signs are so made because black and yellow is the most visible combination of colors.

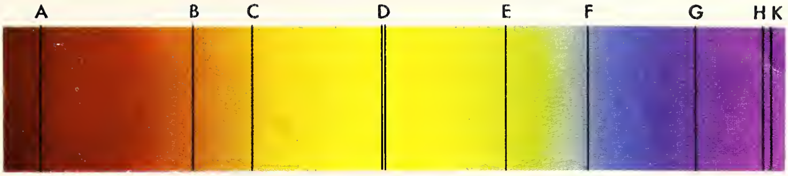
Colors are used also to prevent accidents in factories. At one time all machinery was painted a dull gray or black, because those colors did not show grease. In modern factories, however, the parts of a machine that must be watched constantly are painted a soft color to reduce eyestrain, while moving parts or controls are painted in bright, distinctive colors that attract the eye and warn of danger.

Light Waves

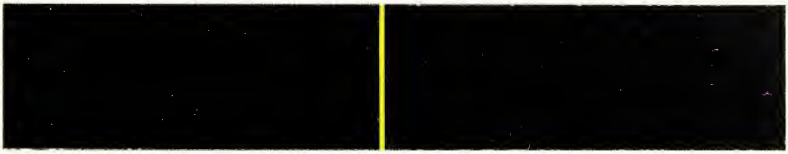
How does light travel through space? So far we have not attempted to answer this question. Scientists believe that both light and heat radiation can travel through space in the form of invisible ***waves***. In fact, we can picture the light radiated from a lamp, for example, as traveling outward in circular waves like the ripples formed when pebbles are dropped into the still water of a pond (Fig. 23-7). But light waves, of course, travel at an enormous speed. Scientists also know that the different colors of the spectrum are caused by light waves of different ***wave length***, which is the distance between two successive crests (Fig. 23-8). For example, the crests of large ocean waves may be separated by 50 feet or more, whereas small ripples are much closer together and may have a wave length of only a few inches. Light waves are extremely close together, as short as one sixteen-millionth of an inch (0.000016 in.). Red light has the longest wave length of the spectrum colors and violet light the shortest. It has been found that ***the greater the wave length, the faster the light travels through glass or water***; thus in glass or water red light travels faster than violet. That is why red light is bent less than violet in traveling through a prism.

The True Nature of Light

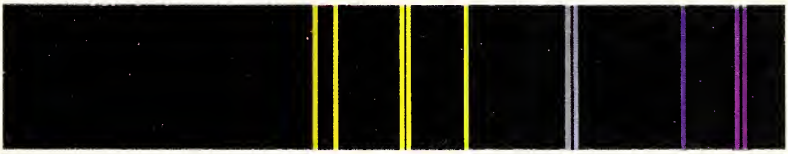
Light waves, of course, are not colored; indeed they are invisible. Then what is color due to? We are aware of the existence of light waves only by their effect. When they are absorbed by the retina they cause



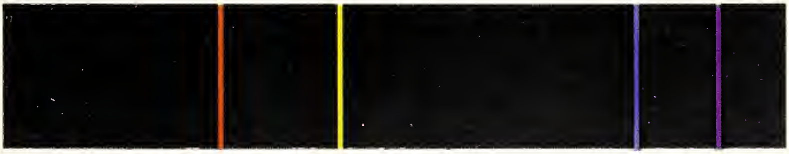
THE SOLAR SPECTRUM



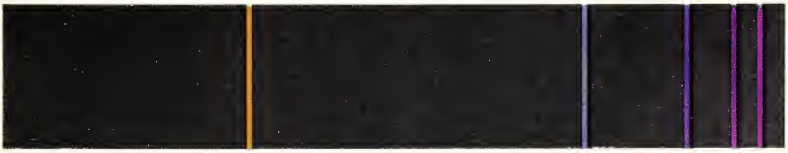
SODIUM



MERCURY



LITHIUM



HYDROGEN

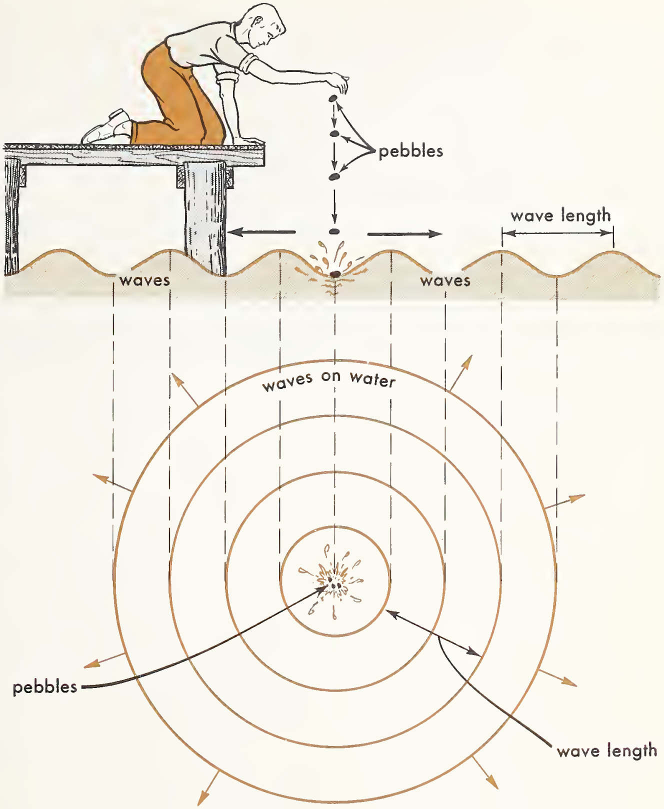


Fig. 23-7. Water waves move out in widening circles when pebbles are dropped into water. The wave length is the distance between two successive crests.

a certain impression, depending on their wave length. This is what we call color.

Newton thought that light was composed of tiny particles that streamed through space from a source of light. Later, scientists found that certain effects produced by light could only be explained by assuming that light was a wave motion. However, in 1900, Planck, a German physicist, showed that the emission of light by an incandescent solid, such as a red-hot piece of iron, could properly be explained only by assuming that light is given off in very tiny bundles called *quanta* or *photons*. Many other effects since Planck's time, such as the operation of photoelectric cells, cannot be explained unless we assume that light is given off in tiny bundles.

Scientists today are confronted with a very ambiguous situation. In order to fully explain the properties of light, they must sometimes consider light as a wave motion and at other times as a stream of tiny particles or quanta or energy. However, most of the common effects produced by light radiation that are discussed in this book can be fairly well explained by considering light as a wave motion.

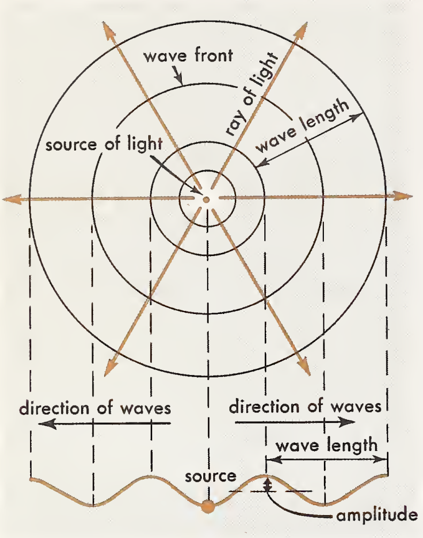


Fig. 23-8. Light waves, like water waves, move out in all directions from a source.

Heat and Color

You may recall that the color of a hot object depends upon its temperature; a yellow-hot object is hotter than a red-hot object, and a white-hot object is hotter than either. Why is this? Hot objects are one of our primary sources of light. *The hotter an object, the more light of short wave lengths it emits.* Thus a white-hot object appears white because it emits light of all visible wave lengths. The sun, for example, gives off white light. The moon, unlike the sun, is cold, and is white only because it reflects all the colors of the light from the sun. Stars, like the sun, are very hot, and their color is due to their high temperature. For example, Betelgeuse and Antares are red stars; Vega is a blue-white one.

An object that is black absorbs all the colors that fall on its surface; it reflects little or no light. Black, therefore, is simply the absence of light. In the chapter on radiation it was stated that a white surface is a very good reflector of heat, while a black surface is a very good absorber and radiator but a poor reflector of heat. In other words, both the color of a surface and the heat radiated from it are the effects of waves differing only in wave length.

The Spectroscope

Newton's method of obtaining a spectrum was not very satisfactory because the colored bands were not sharply separated and focused. They overlapped. Better results can be obtained with a *spectroscope* (see Fig. 23-9) in which the light to be examined passes through a fine slit placed at the principal focus of a convex lens. If a prism is placed in the beam just beyond the lens, the light is separated into its spectrum colors. The slit and lens are enclosed in a tube called the collimator and the separated rays from the prism are viewed through a telescope that gives a sharply focused image of the slit–a separate image for each separate color. Sometimes a photographic film is used to take a picture of the spectrum that is produced.

Different Kinds of Spectra

If we view an incandescent solid such as an electric light filament through a spectroscope, we obtain a *continuous spectrum;* that is, we see all the colors from red to violet. But if we examine a red neon light we find that the spectrum consists mostly of red, orange, and green lines. That is, not all wave lengths of light in the visible spectrum are present. Each line of color is an image of the slit. This is called a *bright-line spectrum.* All incandescent vapors produce bright-line spectra. The incandescent vapor of every known element has been examined, and it is found that *the spectrum of each element is different from that of every other element.* Thus each element, like each human being, can be identified by its own set of "fingerprints."

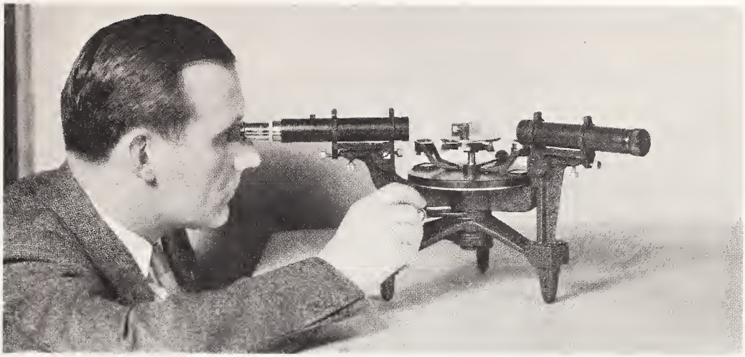


Fig. 23-9. A prism spectroscope. The prism is on the platform in the center between the telescope through which the man sees the spectrum and collimator (on the right). The source of light whose spectrum is to be examined is placed in front of a narrow slit in the right-hand end of the collimator. If a permanent record of the spectrum is desired, the eyepiece of the telescope is replaced by a photographic plate.

Some Uses of the Spectroscope

The spectroscope has given us an amazing amount of valuable information. The chemist uses it as a means of detecting minute traces of elements. If he has only a speck of an unknown substance, he vaporizes it in a flame and photographs its spectrum. Then, by comparing the spectrum obtained with the known spectra of the elements, he can determine which elements are present. In this way, several new elements have been discovered.

The actual wave length of the lines present in the spectra of different elements have given scientists new knowledge concerning the arrangement of electrons about the nucleus in different atoms. It is the disturbance of these electrons that is responsible for the light that is produced.

The most fascinating research, however, has been the examination of spectra obtained from the sun and stars by mounting a spectroscope on a large telescope. These spectra tell us not only the kind of atoms present in the stars, but, because the wave length of light changes when the source is in motion, we can also determine the speeds at which stars are moving away from us and how fast they are rotating. We find that the sun and stars contain, in general, the same kind of atoms as the earth. During the past century, however, one element, identified by its spectrum, was found in abundance on the sun, although it had not been found on the earth. Later, it was found in small quantities on the earth. This is the element ***helium*** (the word helium comes from the Greek word *helios,* meaning "sun").

Invisible Light

We have seen that the visible spectrum extends from the red to the violet. At both ends it fades into darkness. This shows that there are no visible rays beyond the red or the violet, but it does not prove that there are no rays of any kind beyond the visible spectrum. Actually, the visible spectrum is only a very small part of an extensive spectrum called the ***electromagnetic spectrum***.

Infrared Light

A sensitive thermometer placed just beyond the red end of the spectrum indicates that there is heat or ***infrared*** radiation in

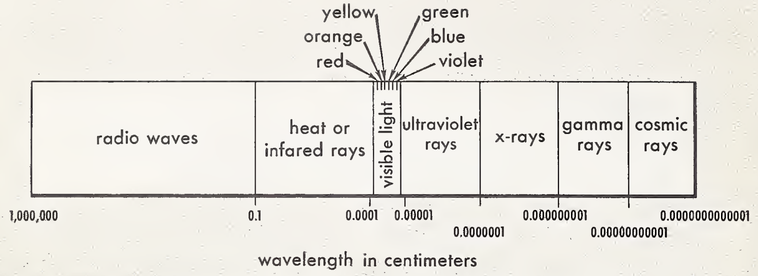


Fig. 23-10. The electromagnetic spectrum. The wave lengths are given in centimeters.

this region. A hot iron in a dark room cannot be seen because it gives off no visible rays. Nevertheless, it gives off infrared rays which can be felt as heat. Although invisible to the eye, they affect special photographic film sensitive to infrared, and it is possible to take a photograph of the hot iron in the dark room.

Infrared rays can also be used for photographing landscapes. This is done by using a red glass filter on a camera equipped with infrared-sensitive film. The filter allows red and infrared to get into the camera, but no other colors. Infrared can pierce fog and haze; it is not scattered by dust in the air like the shorter wave lengths of visible light and, as a result, the distant objects in the picture are sharp and clear.

Ultraviolet Light

A photograph of a spectrum taken on an ordinary photographic plate shows a band extending well beyond the visible spectrum. The light causing this band is called *ultraviolet light* and, like infrared, it is invisible. Some ultraviolet rays cause sunburn. They are useful, however, and the healthful effects of sunlight are due largely to ultraviolet. Ultraviolet light can also trigger many types of chemical reactions. It is ultraviolet light that changes oxygen to ozone at extremely high altitudes in the earth's atmosphere.

The Electromagnetic Spectrum

The different kinds of light we have discussed make up the *electromagnetic* spectrum. Fig. 23-10 shows the types of radiation that make up this spectrum. Note that the wave lengths of visible light occupy only a small portion of the whole range.

The longest waves shown in the electromagnetic spectrum are *radio waves*. Waves that are slightly shorter than ultraviolet are called *X rays*. They are generated in a vacuum tube called an X-ray tube, when high-speed electrons collide with atoms of a heavy metal on a *target*. Because they can

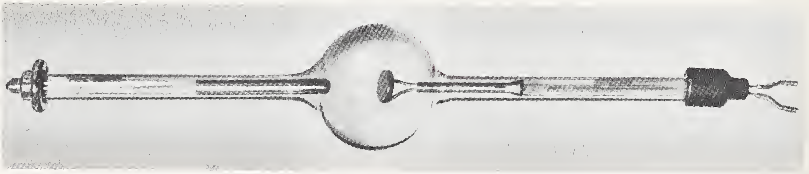


Fig. 23-11. An X-ray tube. Electrons are accelerated from the *cathode* (left end of bulb) by many thousand volts. They strike the circular metal *anode* (center of bulb), causing invisible X rays to be emitted out through the glass walls of the bulb.

penetrate materials opaque to visible light, they are used to examine broken bones in the body and to locate foreign objects in it that cannot be seen otherwise. X rays are also used in industry for detecting cracks and flaws inside metal castings. ***Gamma rays***, which are of even shorter wave length than X rays, are given off by radioactive substances. ***Cosmic rays***, still shorter in wave length than gamma rays, are very energetic, and are produced by the collision of very high-speed atoms that penetrate the atmosphere from outer space with atoms in the earth's atmosphere.

All the different types of radiation in the spectrum are called ***electromagnetic*** because they result from the changing electric and magnetic fields in the atoms which, in turn, are caused by the disturbance of the electrons in the atoms.

Fig. 23-12. A modern million-volt X-ray tube.

Things to Remember

White light can be split up by a prism into a ***spectrum***, which consists of red, orange, yellow, green, blue, and violet light.

Different colors are composed of light waves of different wave length.

Of visible light, ***red light*** has the longest and ***violet light*** the shortest wave length.

A ***prism*** bends red light the least, and violet light the most.

Infrared light has a wave length too long to be seen by the eye.

Ultraviolet light has a wave length too short to be seen by the eye.

X rays are of shorter wave length than ultraviolet light.

The ***color*** of an object that is nonluminous is the color of the light it reflects when white light falls on it.

The sky is blue because some blue light from the sun is ***scattered*** by dust and air molecules in the atmosphere.

Solids give off a ***continuous spectrum*** when they are incandescent.

Gases give off a ***bright-line spectrum*** when they are heated.

Each element, when in the gaseous state and incandescent, emits its own individual line spectrum.

A *spectroscope* may be used to identify the elements of which a substance is composed and to identify the elements on the surface of the sun and stars.

Questions

Part A

1. What are the colors that make up white light?
2. How may light be split up into the colors of which it is composed?
3. What is [**a**] infrared light, [**b**] ultraviolet light?
4. What are X rays and what are they used for?
5. Why is [**a**] a red dress red, [**b**] black paint black?
6. How was helium first discovered?
7. What visible color has [**a**] the longest wave length, [**b**] the shortest wave length?
8. How does the spectrum of a gas differ from the spectrum of a piece of hot iron?

Part B

9. Describe, with the aid of a diagram, the formation of a rainbow.
10. Why does a dark-blue suit appear nearly black when seen under artificial light?
11. [**a**] What is a spectroscope?
    [**b**] How is it used?
    [**c**] What is it used for?
12. A beam of light passes through a prism. What happens and why? Make a diagram.
13. Why is the sky blue?
14. What is the cause of colored sunsets?
15. At very high altitudes, in the stratosphere, the sky appears to be a deep, dark violet –almost black–in the middle of the day, and the sun appears to be much brighter and whiter than when seen from the ground. How can you explain these facts?

Things to Do

Combining colors to make white light

Make a color wheel by cutting out a circle of cardboard about 6 inches in diameter. With a pencil divide it into three equal pie-shaped segments. Paint one segment bright red, another bright green, and the third bright blue. Now mount the wheel on a nail stuck through the center and, holding on to the nail, spin the wheel rapidly by hand in a strong white light. The three colors should combine to give nearly white light, that is, the wheel, while spinning, should appear nearly white or light gray.

Newton split up white light into its component colors. This experiment does just the opposite. The colors from the two ends and the middle of the visible spectrum combine to give white light. We see white light here because of a property of the eye called *persistence of vision*, which means that when we see an object and then it suddenly disappears or moves, we continue to see it in its original position for a fraction of a second after it has left. It is this persistence of vision that makes the rapidly changing pictures of movies and television blend into a smooth-moving picture. In this experiment a given colored segment rotates so fast that, because of persistence of vision, we see a complete circle of that color. The same is true for each of the three segments, so that the three colors combine in the eye to give an impression of a white disk.

UNIT VI

Transportation

24

Steam Engines

We have seen how, in the course of history, man tamed animals, harnessed the power of wind and running water, and invented machines in the never-ending search for ways to have more work done for him. The use of fuels such as wood and coal offered an entirely new attack upon the problem. Could the chemical energy stored in fuels be used to do work? We recall that one cubic foot of water forms about 1700 cubic feet of steam. Thus the obvious approach was to burn coal, boil water, and confine the steam so that steam pressure could be put to work. But this meant the invention of a new kind of machine—a steam engine. Let us examine some of the formidable problems that faced the men who first tried to convert heat into useful work in the eighteenth century.

A Steam Engine

The essential parts of all the early steam engines were a boiler, a cylinder, and a

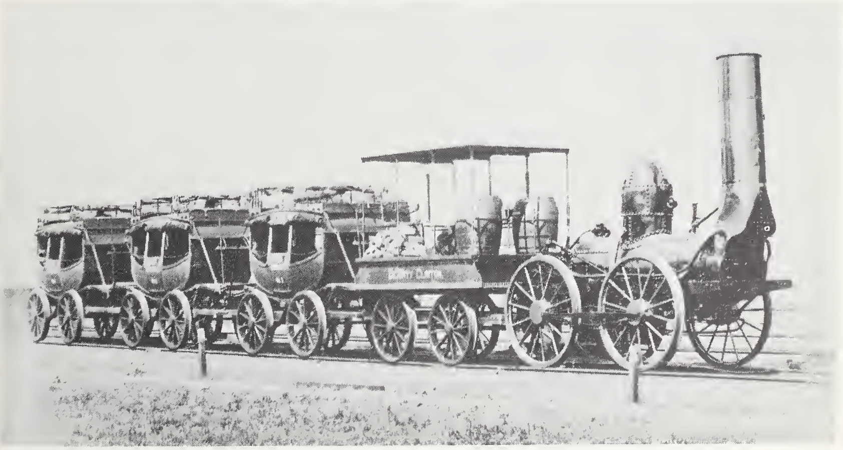


Fig. 24-1. This was the first locomotive to run in North America (in 1831). Notice the fuel (wood) stacked behind the engine. Flying embers from the engine frequently ignited the passengers' clothing.

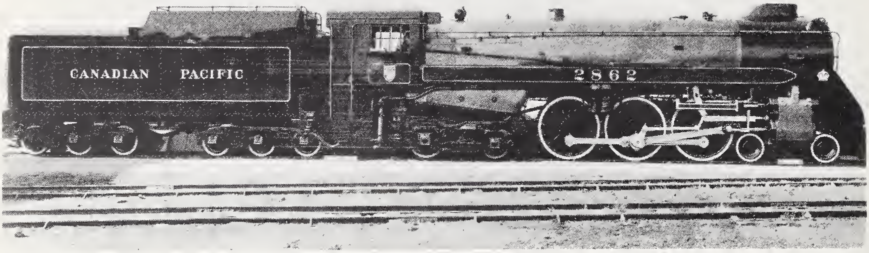


Fig. 24-2. A locomotive is simply a steam engine on wheels.

piston. The steam in the boiler develops a pressure so that it can move a piston in a cylinder. To do useful work, however, the piston must move back and forth, and therefore steam must enter first one end of the cylinder and then the other. A working model of this arrangement is shown in Fig. 24-3. The back-and-forth motion of the piston is called ***reciprocating*** motion.

The first practical steam engine was invented at the beginning of the eighteenth century by an Englishman named Newcomen. Newcomen's engine was a crude machine and very wasteful of coal and steam. Nevertheless, it was used for 70 years to pump water out of coal mines. In 1770 Newcomen's engine was greatly improved by James Watt, a Scottish engineer. For many years Watt's engine was used to operate stationary machinery; that is, to drive machinery in factories, to turn the potter's wheel in making vessels out of clay, to operate lathes in sawmills, and to prevent flooding in coal mines.

The next step was to make an engine that would move, one that would compete with horse-drawn vehicles on land and sailing ships at sea. Such an engine was invented in the early part of the nineteenth century. The first steam-driven vehicle was a steamship, not a land vehicle. Fulton's original steamboat, the *Clermont,* made its first trip from New York to Albany on the Hudson River in 1807; the first crossing of the Atlantic by steamship was made in 1819. The first locomotive was not built until 1830; it weighed 4½ tons and traveled at 30 miles an hour between Liverpool and Manchester in England, hauling a single open coach of 30 people.

Reciprocating steam engines remained the chief source of mechanical energy for more than a century. Today the reciprocating engines of locomotives are being rapidly replaced by diesels. Nevertheless, steam locomotives are still used on many railroads, and reciprocating steam engines are used in many small stationary power plants. Reciprocating gasoline engines are still used in automobiles and planes.

A Locomotive

A locomotive is simply a steam engine on wheels. The cylindrical boiler of a locomotive is horizontal and there is a firebox, where coal or oil is burned, at one end of it. Flames from the burning fuel pass through long tubes, called ***fire tubes***, which run the whole length of the boiler. The waste gases and smoke escape through a smokestack, or chimney. Water completely surrounds the fire tubes and is continuously converted into steam (see Fig. 24-4).

Steam is led into a cylinder and moves a piston back and forth. A piston rod is attached to a drive shaft and this, in turn, is connected to a driver wheel by an off-center device called an eccentric. The drive shaft and eccentric change the back-and-

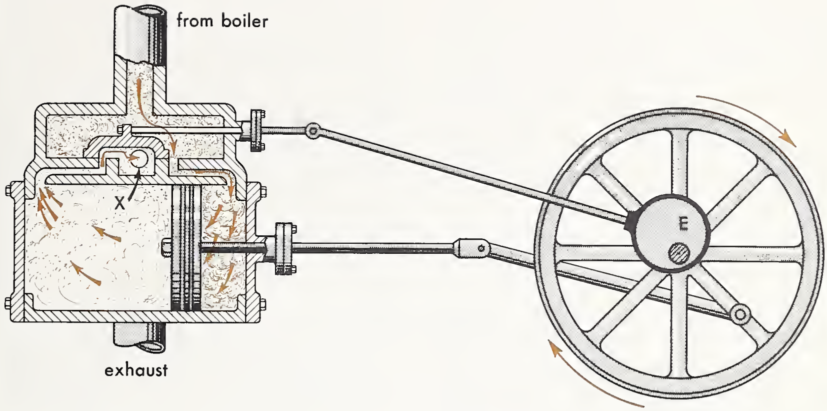


Fig. 24-3. A reciprocating steam engine.

forth motion of the pistons to the rotary motion of the wheel. A locomotive is an exceedingly heavy vehicle; it may weigh as much as 50 tons, and it needs 10 or 12 wheels to support it. Usually four of these wheels receive power, that is, they are directly attached to the pistons through drive shafts.

The Cylinder

Steam in the boiler is under such high pressure that its temperature is about 700°F. When the engineer opens the throttle valve, high-pressure steam flows from the boiler to a steam chest just above the steel cylinder. Two ducts lead from the steam chest to the cylinder, one at each end. A moving slide valve first covers and then uncovers the ducts so that steam is led first to one end of the piston and then to the other. The operation of piston and slide valves can be followed by reference to Fig. 24-3. In the figure, steam has entered the right duct and is pushing the piston to the left. At the same time, the

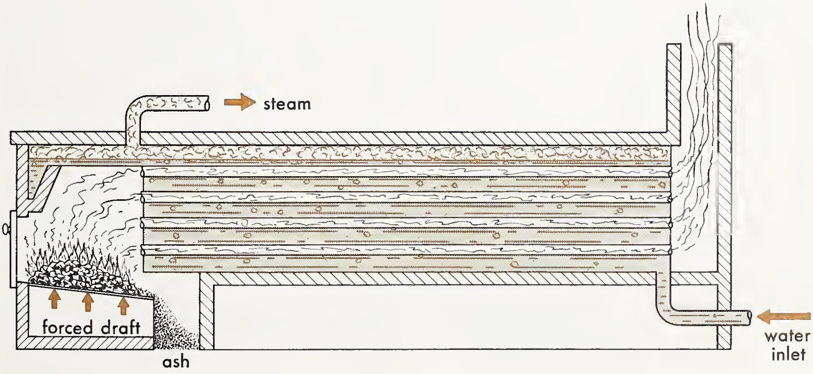


Fig. 24-4. A fire-tube boiler. Flames pass through the tubes which are surrounded by water.

slide valve is being moved to the right so that steam can ultimately enter the cylinder by the left duct. As the piston moves left, the crankshaft, operated by the back-and-forth motion of the piston rod, rotates the wheel. The rotary motion of the wheel then pushes the slide valve back and forth by means of another crankshaft and eccentric. Spent steam from the cylinder escapes through the exhaust port X.

Efficiency of Steam Engines

As the steam in the cylinder expands it does work and, at the same time, it cools because heat energy is transferred from the steam to the engine. That is to say, ***work is done by a steam engine because steam expands and cools;*** if the steam did not cool it would lose no energy and could do no work.

A steam engine is surprisingly inefficient. Only about 20 per cent of the heat of the fuel is converted to useful work, and the rest is wasted. How can we account for these enormous heat losses? Although the boiler and steam pipes are insulated, a great deal of heat escapes from them by radiation. Another factor is that the whole engine is hot and loses heat by convection and radiation. The hot gases which escape through the smokestack constitute another loss and, finally, a great deal of heat is wasted when steam is discharged into the air. (Even though the steam cools in doing work, its temperature is still above 100°C when it is discharged.)

A Steam Turbine

At the beginning of the present century, reciprocating engines produced most of the power for operating machines. However, in 1890, a new engine, a steam turbine, had been invented. As it was developed and improved, the advantages of the turbine became apparent and, for most purposes, it has now replaced the less efficient reciprocating engine.

A steam turbine is really a combination of a Pelton wheel and a windmill. You may have noticed that the blades of a windmill are turned in such a way that they catch the wind; the force of the wind pushes them sideways and rotates the wheel. The same is true of a steam turbine. Here high-pressure steam strikes the blades, pushes them sideways, and rotates the shaft. Before examining a turbine in detail, let us show that high-pressure steam can rotate a wheel.

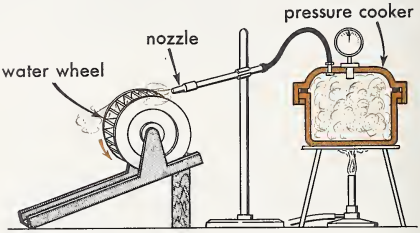


Fig. 24-5. High-pressure steam from the pressure cooker spins the turbine at high speed.

Experiment

23-1. A simple turbine

Attach a glass jet to a heavy rubber tube and tightly fasten the other end of the tube to the safety vent of an old fashioned pressure cooker as shown in Fig. 24-5. Pour a little water in the cooker, fasten the lid securely, clamp the glass jet near the rim of a water wheel, and then heat the pressure cooker. Direct the steam against the vanes of the wheel, bearing in mind that high-pressure steam can produce painful burns. With proper adjustment the wheel can be made to rotate at an amazingly high speed.

The Working Principle of a Turbine

A large steam turbine in action is a raging inferno. High-pressure steam (the pressure may be as great as 2000 pounds per square inch and the temperature as high as 1000°F) escapes through nozzles and strikes against a circular row of blades on a wheel. Behind this row of blades is a second and a third row, sometimes even 20 or 30 rows. The wheels increase in size toward the rear and they are all attached to the same shaft. After striking the first set of blades, the steam expands and strikes the second set, expands and strikes the third set, and so on through the turbine. A set of vanes, fixed to the outer case, is mounted between each set of revolving wheels. As steam passes through a set of blades it is strongly deflected to one side, and the fixed vanes are so arranged to guide steam through the next set of revolving blades. The massed effect of steam pressure against thousands of blades can make the shaft rotate at more than 80 revolutions per second. At this high speed, the rim of the large wheel has a velocity of more than 1000 miles an hour, faster than the speed of sound.

Why are the wheels small at the high-pressure end and large at the low-pressure end? Steam expands every time it pushes on a set of blades and, so that it can continue to expand to do work, more and more space must be provided for it as it moves through the turbine. By the time the steam has passed through the turbine it is almost completely spent and its temperature is no higher than body temperature. That is, in pushing its way through a distance of only a few feet, the temperature of the steam drops by almost 1000 degrees.

On leaving the turbine, the spent steam passes into a condenser where it is changed to water. The condensed water is returned to the boiler, reheated and again sent through the cycle. This cycle of operations is essential in operating turbines on large ocean liners. Thousands of gallons of water a day pass through ships' turbines in the form of high-pressure steam. Because of its impurities, sea water cannot be used in boilers so, unless condensed fresh water were used repeatedly, ships could carry only enough water to run the steam engine for short trips.

Today practically all ships—battleships, aircraft carriers, ocean liners, cargo ships, and even atomic submarines—are driven by steam turbines. The speed of a ship's propeller must not be greater than a few hundred revolutions per minute if it is to operate efficiently. Therefore it cannot be attached directly to the shaft of a turbine

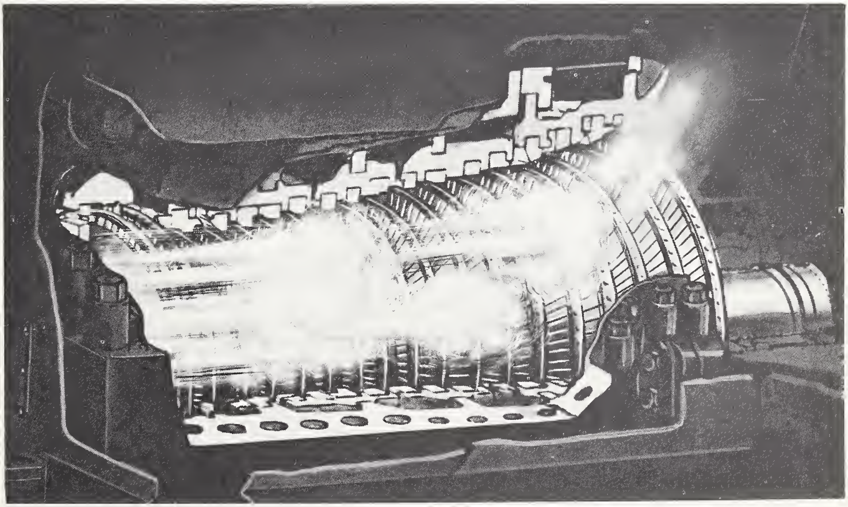


Fig. 24-6. A steam turbine is a raging inferno.

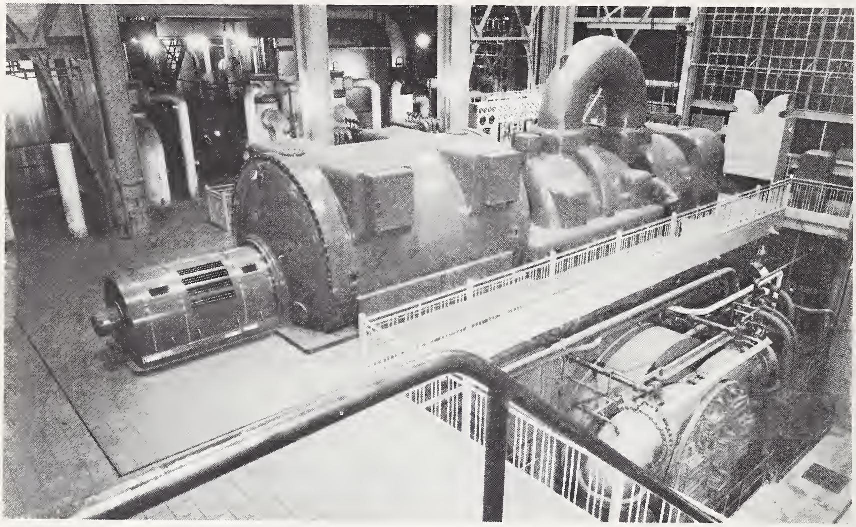


Fig. 24-7. A steam turbine–electric generator combination. The turbine is on the right and the generator on the left.

which rotates at fantastically high speeds. To meet this problem the propeller is connected to the shaft through gears. (Gears are discussed later in the chapter.) The gears reduce the speed of the turbine shaft by the right amount. But we must remember that what is lost in speed is gained in force. As a result, the output force exerted by the propellers is large enough to drive a ship forward at full speed.

A Comparison of Turbines and Reciprocating Engines

Fifty years ago, steam reciprocating engines were used for many purposes which are now served by steam turbines. It is apparent that turbines are generally preferred to reciprocating engines. Why is this? In a reciprocating engine, the back-and-forth motion of the piston must usually be changed to rotary motion before it can do useful work. That is to say, the piston motion is, by some clever arrangement such as a drive shaft and eccentric, made to rotate a wheel. The rotating wheel is then attached to another machine by belts or gears. A turbine, however, gives rotary motion directly so that the drive shaft and eccentric of a reciprocating engine are unnecessary. Therefore, it is not surprising that turbines are cheaper to build than reciprocating engines. Other advantages are that they operate with much less vibration, and are more efficient than reciprocating engines; that is to say, they convert a higher percentage of heat from the fuel (about 30 per cent of it) into useful work.

Because of its high speed of rotation, a turbine is particularly suitable for driving an electric generator. Turbines are the only kind of steam engine used for this purpose. Electricity is cheap and plentiful, and one of the reasons for this is that it is generated from the power of turbines rather than from reciprocating engines. A steam turbine-electric generator combination is shown in Fig. 24-7.

Belts and Gears

We have stated that both the rate of rotation and the input force of a turbine shaft can be changed by gears. What are gears and how do they work? Many kinds of machines are operated by turbines and motors. Electric energy drives a motor; energy of steam drives a turbine: and, in both motor and turbine, a shaft is made to rotate. But how can a motor (or a turbine) be made to operate a machine such as a lathe or circular saw? The motor must, in some way, be attached to the lathe. This attachment could be made by a belt or gears, or it could be attached directly by the central shaft.

In a belt-and-pulley system, one pulley is fitted to the shaft of a motor and another to the shaft of the machine we wish to operate. A belt is then passed over both pulleys. (The fan belt of an automobile is an example of a connection of this kind.) A belt-and-pulley system is a machine; it is a variety of the wheel and axle discussed in Chapter 4. Being a machine, it receives an input force and delivers an output force. The output force may be less than, equal to, or greater than the input force, depending on the size of the pulleys.

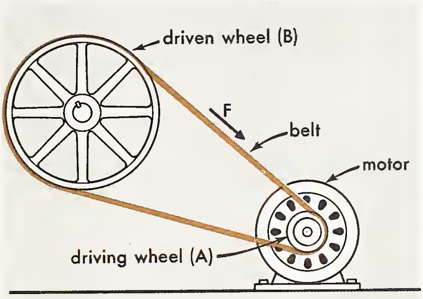


Fig. 24-8. A motor can operate a machine if the two are connected by a belt.

The motor-driven pulley is usually called the *driving wheel*, and the machine-operating pulley is called the *driven wheel*. If the two wheels are of the same size, as in Fig. 24-9, they will rotate at the same speed; for every rotation made by the driving wheel, a rotation is also made by the driven wheel. Since there is no change in the speed of the wheels, there is no change in the force transmitted by them. Therefore the mechanical advantage of this system is 1. Why?

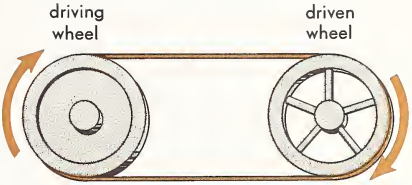


Fig. 24-9. If driving wheel and driven wheel are of the same size, they rotate at the same speed.

Suppose, however, that the driven wheel (B) is greater than the driving wheel (A), as shown in Fig. 24-8. What is the mechanical advantage in this case? As wheel A makes a complete rotation, wheel B makes only a partial rotation; that is, B rotates more slowly than A. Hence B shows a loss in speed but a gain in force. This means that the force produced by the driven wheel is greater than the force applied to the driving wheel and, therefore, the mechanical advantage of the system is greater than 1.

In many cases, power is transmitted from one machine to another by gears instead of belts. Gears, like belts and pulleys, are machines for gaining force and losing speed, or vice versa. They consist of interlocking teeth meshed together. You have no doubt seen them in the "works" of a clock or watch, and in the next chapter we shall discuss gear systems in automobiles.

If the gear system consists only of two gears, the direction of rotation of the driven gear is opposite to that of the driving gear as shown in Fig. 24-10. Notice that, in this example, the driven gear is smaller than the driving gear. Therefore, the driven gear rotates more rapidly than the driving gear. Hence this gear system gives a gain in speed and a loss in force, and its mechanical advantage is less than 1.

To rotate driving and driven gears in the same direction, a third gear, called an idler

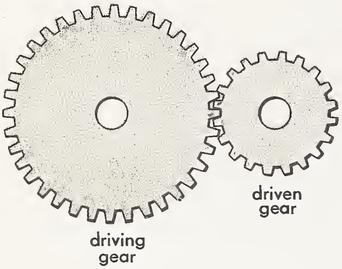


Fig. 24-10. This gear system has a mechanical advantage less than 1. Why?

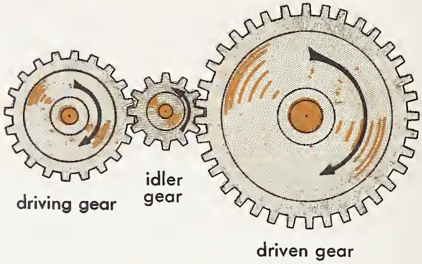


Fig. 24-11. An idler gear enables driving and driven gears to rotate in the same direction.

gear, must be placed between them. Such an arrangement is shown in Fig. 24-11. The driving gear transmits rotation opposite to that of the idler gear and the idler transmits rotation opposite to that of the driven gear. Therefore driving and driven gears rotate in the same direction. If these two gears are of the same size they will rotate at the same speed and without any change in force, whatever the size of the idler gear. Is there any change in force in the gear system shown in Fig. 24-11? Is the mechanical advantage of this system greater than, equal to, or less than 1?

Things to Remember

A ***reciprocating engine*** is one that gives back-and-forth motion of a piston.

A ***steam turbine*** gives rotary motion to the turbine shaft.

Work done by a steam engine is caused by the expanding and cooling of high pressure steam.

A turbine (or motor) may be indirectly attached to a machine by a ***belt*** or ***gears.***

Gears are machines; they consist of wheels with interlocking teeth.

Questions

Part A

1. What is a reciprocating engine? Give an example.
2. What is meant by the term *efficiency* as applied to a steam engine?
3. Why is sea water used in condensers on ships but not in boilers?
4. Explain how a belt may be used to transmit power from a turbine to a device such as an electric generator.
5. What is [**a**] a gear, [**b**] an idler gear?

Part B

6. What are some similarities and differences between a water turbine and a steam turbine?
7. Explain how and why high-pressure steam does work in the cylinder of a steam engine. Draw a diagram.
8. How do you account for the fact that the efficiency of a reciprocating steam engine is not more than 20 per cent?
9. How does a steam turbine work? Explain why turbine wheels are made larger toward the rear of the turbine.
10. What are the advantages of a turbine over a reciprocating engine?
11. Draw two belt-and-pulley systems, one to give a gain in force, and the other to give a gain in speed. Label the driving and driven wheel in each case.
12. Draw and label a gear system in which the driven gear rotates at half the speed of the driving gear, and in the same direction.
13. Explain clearly why the gear system in Question 12 gives a gain in force.

Things to Do

A Belt-and-Pulley System

Using a nail, fasten a large spool loosely to the upper part of a slab of wood. The nail is used as an axle so that the spool is free to turn. Place a stout rubber band over the spool and now, using another nail as an axle, fasten a small spool in the lower part of the wood. This nail should be in such a position that the rubber band will be tightly stretched by the spools. Now slip the rubber band over the two spools.

Rotate the large spool through a complete turn. Is the rotation of the small spool greater or less than a complete rotation? Assuming the input force is applied to the larger spool, is the mechanical advantage greater or less than 1? Assuming the input force is applied to the smaller spool, is the mechanical advantage greater or less than 1?

25

Internal-Combustion Engines

Steam turbines and reciprocating steam engines are *external-combustion* engines, which means that the fuel is burned outside the cylinder. An engine would clearly be far less cumbersome if the boiler could be dispensed with and if the fuel could be burned inside the cylinder and the combustion gas used to push the piston. The early investigators hoped that such an *internal-combustion* engine might be light enough to be used in a self-propelled vehicle that could run on highways rather than on special tracks.

What were the problems that faced the engineers who attempted to design this new kind of vehicle? First, there was the combustion problem. You will recall that the first oil well was drilled in 1858. In those days kerosene was distilled from the crude oil and used for illumination. The gasoline fraction was too dangerous to use in oil lamps and was thrown away. But gasoline promised to be an ideal fuel for the new engine. It would ignite easily because its kindling temperature was relatively low. But how could this be done inside a cylinder? An ignition coil and spark plug were needed. This device had to give sparks in rapid succession, suitably timed, so that an explosion of the gasoline-air mixture would take place at the right moment. But *liquid* gasoline will not burn; only the vapor will do this. Hence another device was necessary to vaporize the gasoline before it entered the cylinder. This device is a ***carburetor***. In addition, the carburetor must mix the vapor with the proper amount of air. The familiar insect sprayer illustrates the working principle of a carburetor.

Experiment

25-1. To operate an insect sprayer

Pour some water into the glass reservoir and attach it to the sprayer. Move the piston back and forth, and notice that water rises up the narrow tube in the container and escapes as a spray.

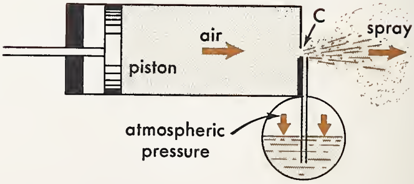


Fig. 25-1. An insect sprayer. Water is caught in the air stream, forming a fine spray.

What forces water up the tube? As the piston is pushed forward, air is forced through the opening C (see Fig. 25-1) and across the open end of the tube. The rapidly moving air greatly reduces the pressure at C. (This reduction of pressure is the so-called ***Bernoulli effect***, and is discussed on page 252.) The pressure of the atmosphere, exerted on the water surface in the reservoir, forces water up the tube; the water is caught in the air stream and broken up into droplets to form a fine spray.

The Carburetor

Gasoline, from the tank at the rear of an automobile, is pumped into the reservoir of the carburetor. A needle valve attached to a float controls the level of the gasoline and prevents the reservoir from becoming too full. The valve is fixed to a rod, one end of which is pivoted to the inside wall of the reservoir, while the other end supports a float. As gasoline enters the reservoir, the float rises until, eventually, the needle valve closes the opening. Then no more gasoline can enter. Gasoline leaves the reservoir by a tube near the bottom. When this happens, the float and also the needle valve are lowered so that more gasoline enters the reservoir.

The tube from the reservoir leads into a narrow section, or constriction, in the air intake pipe. This narrow tube becomes wider above and below, and is called a ***venturi***. Air from outside rushes through the constriction much faster than it flows through the wider part of the tube. Why is this? As in the case of the insect sprayer, air pressure is reduced in the fast-moving air in the constriction. However, the air in the reservoir is at atmospheric pressure, and therefore gasoline is forced into the air stream where it evaporates almost instantly. The air and gasoline vapor are carried into a pipe called the intake manifold and from the manifold the mixture passes through the intake valves and into the cylinder. It should be noted that far more air than gasoline is used in the combustion process—about 15 parts by weight of air to 1 part of gasoline, or, expressed another way, about 8000 gallons of air per gallon of liquid gasoline.

A throttle valve controls the total flow of fuel-air mixture. The throttle is controlled by the accelerator pedal. If this is depressed, the throttle is opened wider and more of the gasoline-air mixture enters the cylinder. The additional fuel provides the extra power needed to climb a hill or to accelerate the car on a level road.

An Internal-Combustion Engine

In the gasoline-air explosion, carbon dioxide and water vapor are the gaseous products of a reaction in which a temperature of almost 4500°F is reached. These hot gases at high pressure force a piston

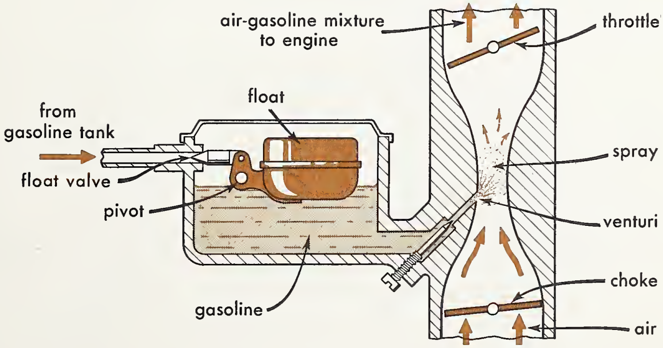


Fig. 25-2. A carburetor vaporizes gasoline and mixes air with gasoline vapor.

down a cylinder. As the hot gases expand, they cool; some of their heat energy is converted into mechanical energy and used to move the car.

Of course there was still much more to be done before the engine could drive an automobile. Power had to be transmitted from the crankshaft to the rear wheels through a number of complicated stages; first to the clutch, then through the transmission, drive shaft, and differential, and finally through the rear axles to the wheels. All these presented engineering problems which took many years to solve. The first automobile was built in North America in 1893, and today, as you know, there are millions of motor vehicles on the highways.

A Four-Stroke Engine

As the piston moves down the cylinder, the intake valve is opened (and the exhaust valve closed) and the gasoline-air mixture is forced into the cylinder by atmospheric pressure. This is the ***intake*** stroke. When the piston reaches the bottom of its stroke, the intake valve closes. The piston then moves up the cylinder with both valves closed, and the fuel mixture is compressed. This is the ***compression*** stroke. When the piston reaches the top of its stroke, a spark from the spark plug ignites the mixture, a combustion reaction takes place, and the expansion of the hot gaseous products drives the piston down the cylinder. This is the ***power*** stroke. The piston now moves up the cylinder, the exhaust valve opens, and the waste gases are forced through the valve and out of the exhaust pipe. This is the ***exhaust*** stroke. This completes the cycle; the exhaust valve closes, the intake valve opens, and the piston is now ready to begin the next intake stroke and another cycle.

A cycle therefore consists of four strokes, intake (I), compression (C), power (P), and exhaust (E) as shown in Fig. 25-4. Of the four strokes, two up and two down, in the four-stroke engine of an automobile, only one delivers power. Or, expressed another way, there is one explosion in a cylinder for every two revolutions of the crankshaft. What keeps the piston moving through the three strokes of the cycle that do not deliver power to the flywheel? An automobile engine may consist of four, six, eight, or even twelve cylinders, all used to drive a single crankshaft and so timed that one or another of them is delivering power all the time. Let us consider the simplest case of four cylinders. Each cylinder produces a power stroke in turn. For example, the strokes of the four cylinders might be arranged as follows:

(1)	I	C	P	E
(2)	P	E	I	C
(3)	E	I	C	P
(4)	C	P	E	I

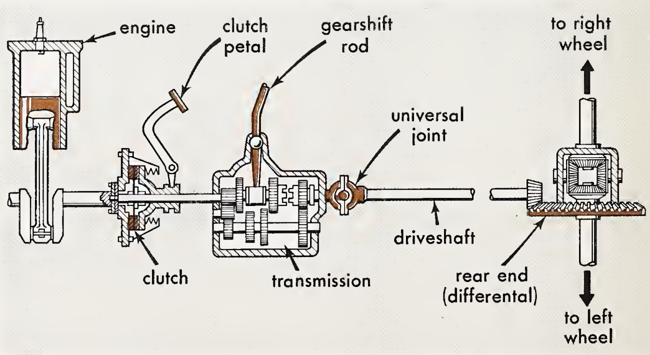


Fig. 25-3. Power from an automobile engine is transmitted to the clutch, then through the transmission, drive shaft, and differential to the rear wheels.

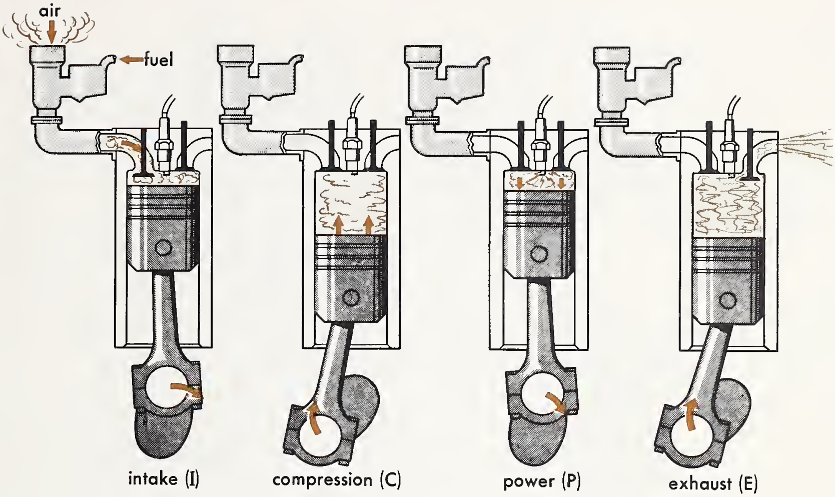


Fig. 25-4. The four strokes of a four-stroke engine are intake, compression, power, and exhaust.

You will notice that no two cylinders do the same thing at the same time; one cylinder takes in the gas mixture while another is compressing it, and still another is exploding it, and still a fourth is expelling the waste gases. All these things happen at the same time. This out-of-step arrangement gives an explosion at every stroke and results in a smooth flow of power from the engine.

One might ask, how is the piston moved through its initial intake and compression strokes *before* the engine develops a power stroke? Before the engine can be started it must be turned over several times to get fuel in the cylinders. The power to do this is supplied by an electric motor called a ***starter***. This motor, which is attached to the flywheel and moves the piston rods, is driven by a storage battery.

The Crankshaft and Flywheel

A piston rod connects the piston with a crank on the crankshaft. The crank changes the up-and-down motion (reciprocating motion) of the piston into rotary motion of the crankshaft. A heavy flywheel mounted on the crankshaft rotates with the shaft. Once the heavy flywheel starts spinning, it tends to keep on spinning. Hence the flywheel helps to keep the engine running smoothly.

The Camshaft

By means of gears the crankshaft also rotates a parallel shaft called a camshaft. Cams are so placed on the camshaft that they move valve rods up and down at the right time. The valve rods in turn open and close the intake and exhaust valves.

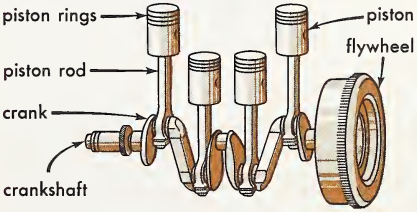
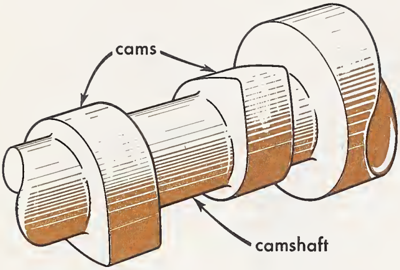


Fig. 25-5. The up-and-down motion of the pistons is changed to the circular motion of the crankshaft.



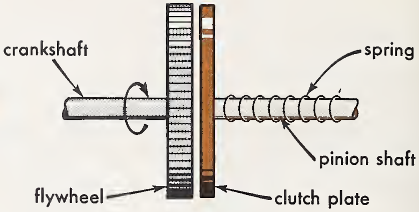


Fig. 25-7. When the clutch plates are engaged, power is transmitted from the crankshaft to the pinion shaft.

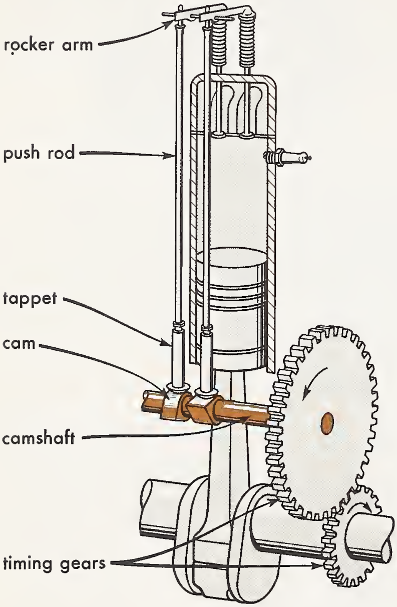


Fig. 25-6. The cams open and close the valves at the right time.

The Clutch

The crankshaft cannot be directly attached to the rear axle, otherwise the rear wheels would turn whenever the engine is running, and it would be impossible to stop the car without turning off the engine. Some device is needed to enable the car to remain stationary while the engine is running, to stop at a traffic light or to change gears while the car is in motion. Such a device is called a ***clutch***.

The clutch consists of two circular metal plates. One is attached to the back of the flywheel and therefore rotates when the engine runs; the other is attached to one end of what is called the pinion shaft. This latter plate is normally held in the forward position (that is, in contact with the other plate) by a strong spring. The rotation of the flywheel plate is thus transmitted to the other plate by friction between them and thence to the pinion shaft. If the clutch pedal is pushed down, the movable plate is pulled from the fixed one and, as a result, the rotation of the engine is no longer transmitted to the pinion shaft. If the pedal is released, the spring again forces the movable wheel forward so that the two become engaged. This rotates the pinion shaft which, through the transmission, rotates the drive shaft.

In some of the newer models, the clutch is replaced by various types of automatic transmission. In the hydraulic or fluid drive, the friction plates of the clutch are replaced by two wheels in a container shaped like a pill box (see Fig. 25-8). Curved blades are attached to the wheels which, in position, are very close together. The container is almost filled with light oil. One wheel is attached to the engine and rotates when the engine is running. This imparts a whirling motion to the fluid so that power is transmitted by the oil and blades to the other wheel which, in turn, rotates.

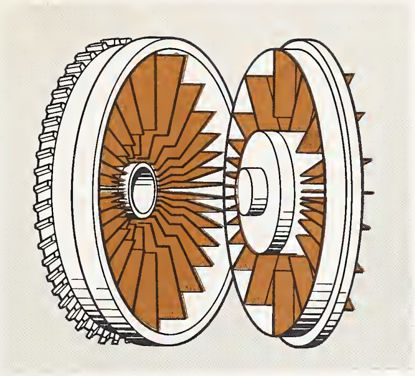


Fig. 25-8. In a fluid drive, clutch plates are replaced by two wheels in a large "pill" box which contains light oil.

The Transmission

If the pinion shaft were connected directly with the drive shaft running to the rear axle, the wheels would rotate at the same speed as the pinion shaft. Sometimes, as in starting the car or climbing a hill, the rotation of the wheels must be slower than engine speed in order to increase the applied force at the wheels. The speed of rotation and direction of rotation is changed by a box of gears and shafts called the ***transmission.***

The transmission consists of three different shafts; the pinion shaft, connected to the engine through the clutch; the countershaft, which is encased in the gear box, and the drive shaft, which is attached to the rear axles through the differential. A driving gear, A (see Fig. 25-10), on the pinion shaft is permanently meshed into a driven gear, D, on the countershaft. Therefore, the countershaft with its gears always rotates when the engine is running; that is, unless the clutch plates are separated. On the countershaft there are, in addition to gear D, three other gears, E, F, and G, of different sizes. Notice that the smallest gear, G, has an idler gear, H, permanently meshed into it. This, as we shall see, is to enable the car to be reversed. Two gears are mounted on the drive shaft. These gears, operated by the gear shaft lever, are free to move back and forth in a slot in the drive shaft. One or the other of these gears can mesh into the gears on the countershaft and so transmit the power of the engine to the rear axles. Let us now examine the gear combinations in the different positions–neutral, low, high, and reverse.

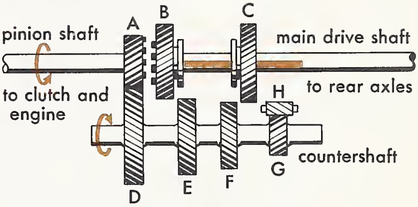


Fig. 25-9. In neutral the gears on the drive shaft and countershaft are not engaged.

Neutral

In neutral, neither of the gears on the drive shaft is meshed with gears on the countershaft. Therefore, no rotation is transmitted to the rear axles and the car is stationary.

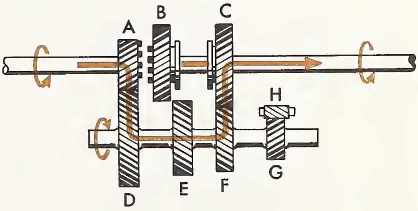


Fig. 25-10. Low gear. The sliding gear, C, on the drive shaft engages the low-speed gear, F, on the countershaft.

Low Gear

To put the car into low gear, the right-hand sliding gear on the drive shaft is moved left until it engages the low-speed gear, F. The heavy lines show how power flows through the gears. Since the low-speed gear, F, is smaller than the sliding gear, C, gear C revolves more slowly than gear F. Hence the drive shaft revolves more slowly than the engine. But what is lost in speed is gained in force. Therefore, low gear has a large mechanical advantage. It is the gear that gives the greatest force at the wheels and that is why, in climbing a steep hill or in starting the car, we usually find it necessary to go into low gear.

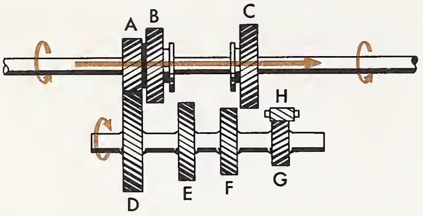


Fig. 25-11. High gear. The sliding gear, B, on the drive shaft engages gear A on the pinion shaft.

High Gear

To go into high gear, the left-hand sliding gear, B, is moved to the left until its projections interlock with those of the driving gear, A. The drive shaft is then connected directly with the engine and rotates with the same speed as the engine. The mechanical advantage of this arrangement is 1. Why?

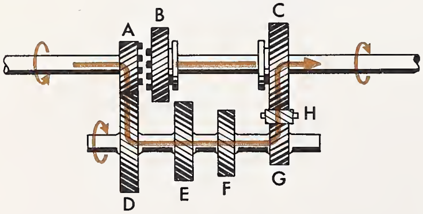


Fig. 25-12. Reverse. Sliding gear, C, on the drive shaft engages gear G on the countershaft via the idler gear, H.

Reverse

To put the car in reverse, the right-hand sliding gear, C, is moved so that it engages the idler gear, H. Hence the rotation of C is the same as G, and opposite to that of the driving gear, A. Therefore the wheels turn backward. Since sliding gear C is much larger than reverse gear G, the drive shaft rotates slowly and the car also goes back slowly. But again there is a gain in force at the wheels; the mechanical advantage of the engine is now larger than in low gear because the reverse gear is smaller in size than the low gear.

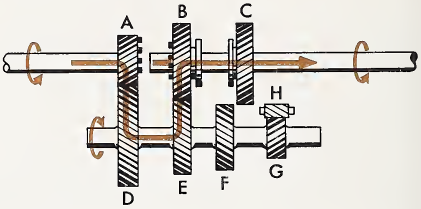


Fig. 25-13. Second gear. Can you explain how it operates?

Second Gear

Still another combination is, of course, "second." The way it operates is shown in Fig. 25-13.

The Differential

Power is next transmitted from the drive shaft to the rear axle. How can this be done, since the drive shaft and axle are at right angles to each other? Force and motion are transmitted in this way by means of beveled gears, as in an egg-beater–a beveled gear on the drive shaft meshes with a beveled gear on the axle. And now one final problem arises. When a car makes a turn, say to the left, the outside wheel (the right) must travel further and faster than the inside wheel (the left). This problem is solved by splitting the rear axle into two parts. Beveled gears are mounted at the free ends of these two

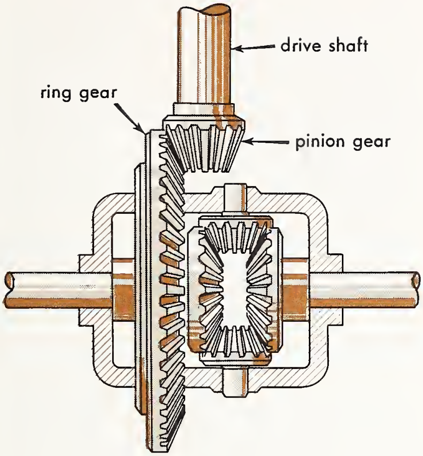


Fig. 25-14. The differential transmits power from the drive shaft to the rear axle.

parts and a third gear, called a differential gear, is meshed into them. This arrangement enables one wheel to rotate faster than the other. Observe Fig. 25-14 carefully, and see if you can figure out how the force of the gear on the drive shaft is transmitted to the left and right axles. The whole of this complicated system of gears is called the differential.

We have now followed the flow of power from the engine through the crankshaft, the clutch, the transmission, the drive shaft, the differential, the rear axles, and, finally to the wheels.

Cooling System

As already stated, the temperature in the cylinder immediately after the explosion is almost 4500°F, a temperature higher than the melting point of steel. Unless the engine is cooled, the moving parts such as valves and pistons, will expand enough to stick. This would stall the engine and might even ruin it. To cool the engine, the cylinder walls are made hollow, and water from the radiator circulates through this space. Hot water from the top of the engine flows into the top of the radiator and passes downward through a "honeycomb" of air-cooled metal tubes. From the bottom of the radiator the water re-enters the engine near the bottom to complete the circuit. To keep the water in circulation, about 5 gallons in all, a pump, driven by the engine, aids the process of convection.

The radiator is in front of the car. As a result, air is forced past the tubes when the car is in motion and the water is cooled. In addition, a fan is placed between the engine and the radiator. The fan draws air through the radiator and drives it against the engine. In this way both engine and radiator are cooled by a blast of air even when the car is not moving (see Fig. 25-15).

Lubrication of the Engine

All the moving parts of the engine must be lubricated, otherwise friction will create

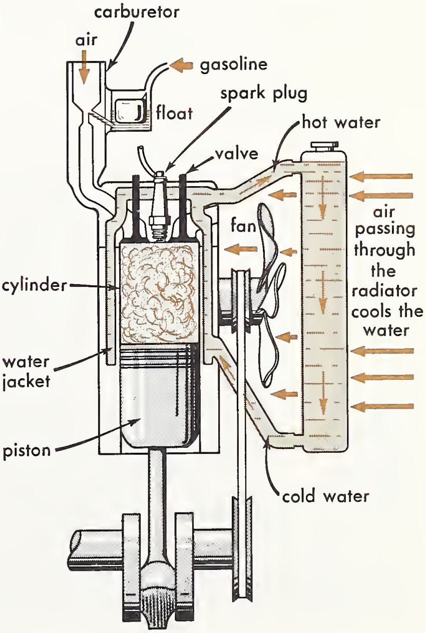


Fig. 25-15. An automobile engine is cooled by air and water.

heat in the bearings, which will rapidly wear out. The same is true of tightly fitting pistons which move up and down the cylinder. Lubricating oil is placed in a crankcase below the engine and, from the crankcase, it is forced through vents and pipes to all friction points in the motor. Piston rings, for instance, spread oil over the cylinder walls, thereby reducing the wear of the surface.

A Gasoline Engine as a Heat Engine

A gasoline engine is more efficient than a steam engine mainly because heat losses from the boiler have been eliminated. Nevertheless, the hot engine loses heat by radiation, by convection in the cooling system, and through the exhaust gases. As a result, the efficiency of a gasoline engine is only about 30 per cent.

In an automobile engine, the compression ratio is usually 7 to 1; that is, the gas mixture is compressed to one-seventh of its original volume. This high compression heats up the gas mixture. Why?

A High-Compression Engine

One of the ways of improving the efficiency of a gasoline engine would be to increase its compression ratio; that is, to compress the gas mixture to less than one-seventh of its original volume. However, a higher compression would raise still further the temperature of the gas mixture before ignition and the fuel would probably ignite before the piston had reached the top of its stroke; that is, before a spark had jumped the gap. This would cause a knock in the engine and reduce its power. At the higher compression, the temperature and pressure of the gas products would be so high that the cylinder walls might not be able to take the extra strain.

These were two of the problems that Rudolph Diesel, a German engineer, solved as he experimented with his high compression engines. The first workable diesel engine was produced in 1892.

The Diesel Engine

To prevent too early ignition of the fuel, Diesel compressed only air, not a mixture of fuel gas and air. Air, of course, will not burn no matter how much it is heated. Then into the hot compressed air he injected fuel oil, not gasoline. This new ignition system was much simpler than the ignition system of a gasoline engine. Why?

In the diesel engine, an ignition system (a spark plug and induction coil) is unnecessary, nor is a carburetor needed. These are replaced by a fuel injector. To prevent the cylinder from bursting under the high compression, Diesel built a much heavier and stronger wall. Even to this day the heavy walls impose limitations on the diesel engine.

A Four-Stroke Diesel

A four-stroke diesel is similar to a four-stroke gasoline engine except that no fuel

Fig. 25-16. A diesel-powered locomotive.

enters the cylinder during the intake stroke. Instead, the pressure in the cylinder is reduced as the piston moves down and, since the inlet valve is open, air from outside rushes into the cylinder. During the compression stroke, air in the cylinder is compressed to about one-eighteenth of its original volume, and its temperature rises to about 1000°F. At the top of the compression stroke a fine spray of oil is injected in the cylinder, by means of a tiny pump called a fuel injector. The oil burns instantly; the temperature of the waste gases rises to about 4500°F, and the pressure exerted on the piston may be as high as 1000 pounds per square inch. It is this tremendous pressure that constitutes the power stroke. After the power stroke, the piston moves up, the exhaust valve opens, and the waste gases are forced out of the cylinder.

A Two-Stroke Diesel

A two-stroke diesel, in which two of the four strokes are eliminated, is in common use. The engines that drive diesel-electric locomotives are of the two-stroke type. Unnecessary strokes are eliminated by making each up-and-down stroke do two jobs instead of one, as in the standard engine. Oil, as usual, is injected into the compressed air and the explosion takes place. However, as the piston approaches the bottom of its stroke, a series of air ports in the cylinder wall is opened and, by means of a blower, fresh air is blown through them and into the cylinder. This

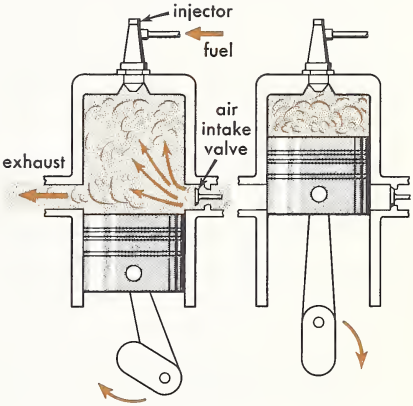


Fig. 25-17. A two-stroke diesel engine.

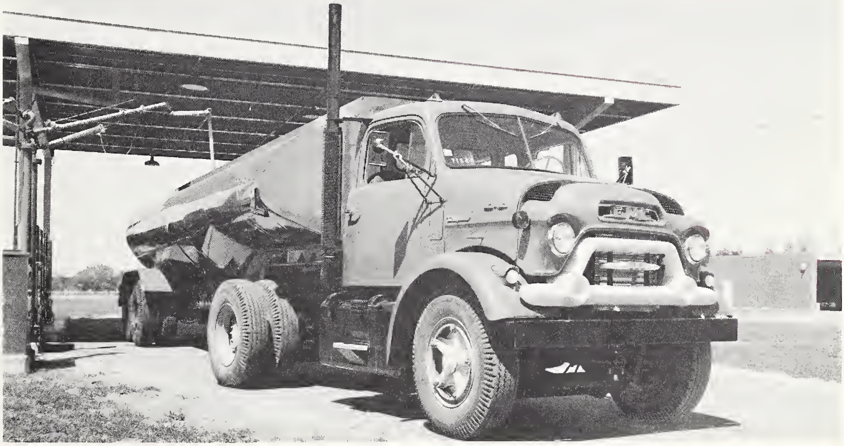


Fig. 25-18. A diesel truck.

stream of fresh air also expels the waste gases from the previous power stroke, through the open exhaust valve. In this way, two different operations are done during one stroke (see Fig. 25-17). The rising piston then closes the air ports and compresses the clean air. By this arrangement, one power stroke is delivered for each revolution of the crankshaft, instead of for every two revolutions as in the four-stroke engine.

A Diesel Engine Compared with a Gasoline Engine

Some of the advantages of a diesel over a gasoline engine have already been mentioned. In addition, the diesel is more efficient than the gasoline engine; its efficiency is as high as 40 per cent, due chiefly to its high compression ratio. The diesel uses fuel oil which is cheaper, more plentiful, and much safer to store than gasoline.

The big disadvantage of the diesel is its great weight, due largely to the heavy cylinder walls made to withstand the high pressures. An average diesel engine weighs at least 15 pounds for each horsepower, and a big diesel may weigh as much as 250 pounds per horsepower. The gasoline engine of an automobile, on the other hand, weighs about 10 pounds per horsepower. An airplane gasoline engine weighs no more than 1 pound per horsepower, whereas diesel aviation engines have not been reduced below 5 pounds per horsepower. These figures explain in part why diesels have not replaced gasoline engines in airplanes and automobiles, and why the use of diesel engines is limited to locomotives, ships, trucks, tractors, buses, and stationary power plants.

Things to Remember

Internal-combustion engines burn fuel inside, rather than outside the engine.

Two common types of internal-combustion engines are *gasoline* and *diesel engines.*

All internal combustion engines burn a *fuel-air mixture.*

In a *gasoline engine*, the fuel-air mixture is ignited by a spark.

In a *diesel engine*, the fuel is ignited by hot compressed air.

Most internal-combustion engines operate on a *four-stroke cycle*: intake, compression, power, exhaust.

Questions

Part A

1. What two types of internal-combustion engine are in common use today?
2. Name the four strokes of a four-cycle engine.
3. What prevents an automobile engine from becoming overheated?
4. What is a two-cycle engine?
5. What is the main difference between a steam engine and an internal-combustion engine?
6. What are the two main differences between a gasoline engine and a diesel engine?

7. Why must a diesel be more ruggedly built than a gasoline engine?
8. The compression ratio of a diesel engine is about 18:1. What does this mean?
9. Why are diesel engines not generally used in airplanes?

Part B

10. Explain how a gasoline vapor-air mixture is obtained in a gasoline engine. Draw a diagram of the apparatus.
11. Describe the sequence of operations in a four-cycle gasoline engine.
12. What is the clutch? What is its purpose? How does it operate?
13. How are the pinion shaft and drive shaft connected in low gear? Is the force on the drive shaft increased or decreased in this operation? Explain.
14. What would be the temperature and pressure effects of increasing the compression ratio of an engine from 8:1 to 16:1. Explain the effects in terms of molecular impacts.
15. Discuss one of the problems Diesel had to solve in designing his new engine.
16. How does a four-stroke diesel engine differ from a four-stroke gasoline engine?
17. [**a**] What are the two sources of heat in a gasoline engine cylinder? Explain.
    [**b**] Compare these sources of heat in a gasoline engine with the corresponding sources in a diesel.

Things to Do

To examine an automobile engine

Obtain an old automobile engine from a local garage or junk yard. Remove it to a convenient place, such as the basement of the school. Clean it carefully with kerosene, and then take it apart. List the parts as you remove them, making simple sketches to show their position in the engine.

Finally, cut away parts of the engine, such as one cylinder wall, the sides of the transmission, and the cover of the drive shaft. Mount the whole engine on a heavy wooden base as a permanent working exhibit for the school.

26

Aircraft

In a locomotive or an automobile, travel is limited to a steel track or highway. A bird, however, has much more freedom of movement; it can control the height and direction of its flight. The next advance in locomotion was therefore to take to the air. But this raised many new problems. How could a heavier-than-air machine be made to fly? The new problems were first successfully solved, about 60 years ago, by two young brothers, Wilbur and Orville Wright. They worked for 12 years on preliminary experiments, most of which were carried out on the sand dunes at Kitty Hawk on the coast of North Carolina. First they worked with a glider and learned that even air currents could, under the right conditions, buoy up a heavier-than-air machine. Then they designed and constructed a plane, complete with engine and propeller. In December 1903, they made their first flight. One brother mounted the plane and operated the engine; the other ran alongside holding one wing to steady the plane until it left the ground. The flying time of the first official flight was only 59 seconds, the distance covered was 852 feet, and the speed about 33 miles an hour. From the Wright brothers' home-made plane have developed all the various types of aircraft we see today.

Bernoulli's Principle

Before we can understand how air lifts a plane, we must first refer to an important discovery made by a Swiss scientist named Bernoulli in 1750. He discovered that *the pressure within a fluid in motion is lower than the pressure outside the stream; and the greater the speed of the stream the less is the pressure within it.* This statement, or principle, as it is called, probably comes as a surprise to us because we are inclined to associate greater speed with greater pressure. However, we can easily verify the statement both theoretically and experimentally. Notice that the principle concerns *fluids* in motion, so that it applies to a flow of water as well as to air. First let us illustrate Bernoulli's principle by considering the flow of water through a venturi tube, a tube that narrows and then widens again.

A venturi tube like that shown in Fig. 26-2 is suitable for our purpose. Notice that a wide tube tapers at B and then widens again at C. Narrow vertical tubes are attached at A, B, and C. These vertical tubes act as pressure gauges. If water flows through the tube, the gauge tubes fill with water until the pressure due to the height of the water column equals the pressure of the flowing water. The water level in the gauge tube B is lower than in the gauge tubes A and C. Hence, the pressure at B is less than the pressure at A or C.

How can we explain the lower pressure at B? Since the tube is filled with water, the same volume of water must pass points A,

Fig. 26-1. This plane, with Orville Wright at the controls, made its first flight in 1903.

B, and C every second. Therefore water must travel faster through the narrow tube at B than the wider tube at A or C. But to speed up the flow in the narrow part of the tube, the pressure behind it must be increased. Therefore, the pressure at A is greater than the pressure at B. Similarly, because the speed at C is less than the speed at B, the pressure at C must be greater than the pressure at B, otherwise it would be unable to slow down the fast-moving water at B.

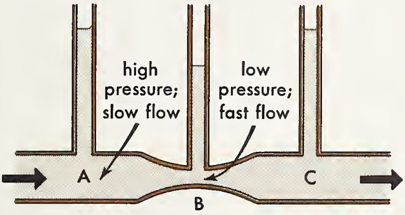


Fig. 26-2. The drop in pressure at the constriction, B, is an example of the Bernoulli effect.

This explanation also accounts for the increased speed of air as it rushes through the constriction in the venturi tube of a carburetor. The high speed causes a low pressure, and a low pressure, you will recall, allows gasoline to be forced out of the carburetor reservoir. Another way of showing the Bernoulli effect in air is as follows:

Experiment

26-1. Pressure in the airstream below a spool is reduced

Stick a pin through a piece of cardboard about an inch square, and insert the pin through the hole of a wooden spool as shown in Fig. 26-3. Hold the cardboard against the spool. Now blow through the other end of the spool and release the cardboard. The air blast makes the cardboard stick to the spool, and the harder you blow, the closer it sticks. Why is this?

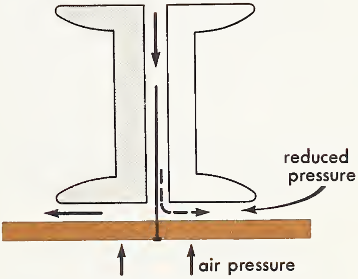


Fig. 26-3. Pressure is reduced in the air stream so that the card sticks to the spool.

Because of the Bernoulli effect, the pressure in the air current flowing through the narrow gap between the spool and the cardboard is reduced. Atmospheric pressure, exerted on the other side of the card, is therefore greater than the pressure in the current and, as a result, the cardboard is pushed against the spool.

This same Bernoulli effect makes it dangerous to stand near a passing train. Can you explain why? The effect of the motion of the train is to reduce considerably the air pressure between you and the train. Consequently, atmospheric pressure exerted on the side of your body away from the train, may be great enough to push you into the moving train, an effect illustrated in the following demonstration.

Experiment

26-2. Suspended ping-pong balls come together in an air stream

Attach a thread to each of two ping-pong balls by Scotch tape. Suspend the balls by the threads at the same height and about two inches apart. Blow gently through a glass tube, directing the air stream midway between the suspended balls. The balls move toward each other and collide. Can you explain why?

By far the most important application of the Bernoulli effect, however, is the lift it gives to an airplane.

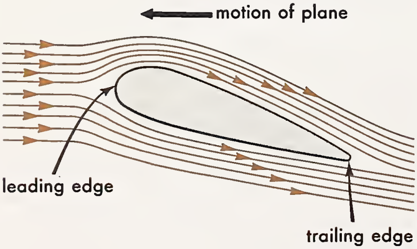


Fig. 26-4. Air is split into two streams by the leading edge of the wing.

How Moving Air Lifts a Plane

By testing model planes in wind tunnels, aeronautical engineers have discovered that the *shape* of the wing is an important factor in determining lift. Let us see why. You may have noticed that the top of the wing is more curved than the bottom. A cross-section of a wing is shown in Fig. 26-4. When air meets the front (or ***leading edge***) of the wing, it splits into two streams, one passing over the wing and the other under it. The two streams then meet behind the rear or ***trailing edge***.

How do these two air streams supply the lift? The air stream over the upper curved surface travels further in the same time than the stream under the lower surface. Hence the upper stream travels faster and, therefore, the pressure in the upper stream pushing down on the wing is reduced more than the pressure in the lower one pushing up. The difference in pressure on the upper and lower part of the wing is called ***lift***. It can readily be demonstrated as follows.

Experiment

26-3. Lift effect of an air stream

Tear a piece of paper about 3 inches by 10 inches. Hold one end of the strip near your chin and blow across the top of it. The paper rises and flutters in the air stream. Can you explain why?

Components of a Force

Most of the lift on a plane (about two-thirds to three-quarters of it) comes from the Bernoulli effect. The rest comes from the force of the wind which pushes up on the underside of the wing. To understand these forces more fully, let us first examine a system of forces we are familiar with—the forces on a lawnmower. To push a lawnmower, a force is exerted on the handle in the direction of the wooden bar, that is, along HA. However, the lawnmower moves horizontally, not in the direction of the push. Hence we say that the

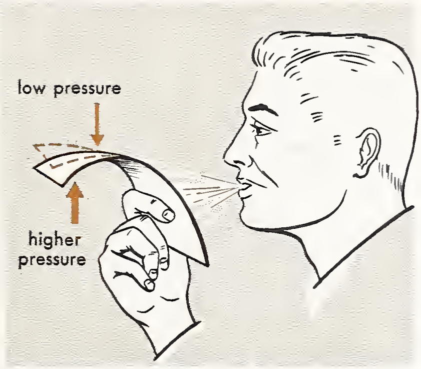


Fig. 26-5. The air stream lifts the free end of the strip of paper.

force HA has a *horizontal component* which moves the mower. To represent the forces diagrammatically, a rectangle is drawn with HA as diagonal. The two sides of the rectangle, HD and HE, represent the components of the applied force HA, the lengths of the arrows being proportional to the strengths of the forces HA, HD, and HE. The horizontal component is the useful force that moves the mower; the component HE is a downward force pushing on the mower. In other words, *the force applied to the mower is resolved into two component forces* which serve different purposes. Let us now apply this principle to the lift on a plane.

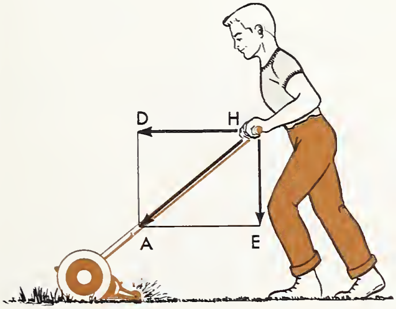


Fig. 26-6. The force HA is resolved into components HD along the ground and HE perpendicular to the ground.

Lift on Underside of Wing

As a plane moves forward, it creates its own wind in a direction opposite to that of the plane. If the wing is tilted, the air stream is deflected downward and backward from the lower surface of the wing as shown in Fig. 26-7. As a result, a lifting force, F_1, which is inclined backward, is transmitted to the wing of the plane.

The Forces on a Plane

The total lifting force on a plane is the combined effects of the Bernoulli lift and the deflection of the air stream as shown in Fig. 26-8. The force F_1 is due to the deflected air stream, and F_2 is the force due to the Bernoulli effect. The total force F ($F = F_1 + F_2$) can be resolved into components L and D, as in the case of the lawnmower. The vertical component L is the force that lifts the plane. The horizontal component D is a force that opposes the motion of the plane; it is a force of resistance known as *drag*.

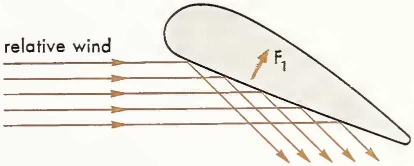


Fig. 26-7. As the air stream is deflected downward, a lifting force, F, is transmitted to the wing of the plane.

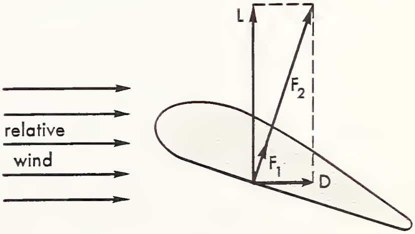


Fig. 26-8. The total lifting force on the wing is due to the deflected air stream, F_1, and the Bernoulli effect, F_2.

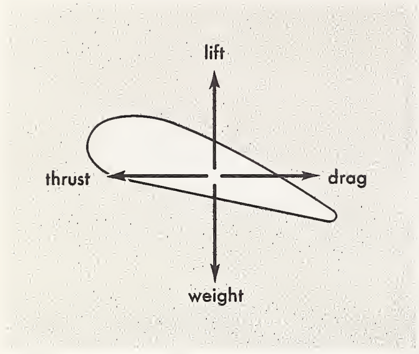


Fig. 26-9. In level flight, thrust balances drag and lift balances weight.

All the surfaces of a plane offer resistance to the air; that is, they all contribute to the total drag. Drag must therefore be matched by the forward thrust of the propeller. Drag can be reduced by streamlining and this is important in designing a plane. The body, or fuselage, is shaped like a fish and the wings are long and thin. Both features are designed to reduce air resistance.

When a plane takes off, the throttle is opened wide. Why is this? At the take-off, the plane must accelerate and climb at the same time. Both these operations need extra power from the engine, and that is why the fuel mixture is fed to the engine more rapidly.

In level flight, two pairs of balanced forces act on the plane; the forward thrust caused by the rotating propeller equals the drag on the wings and body, and the lift on the wings equals the weight of the whole plane. If the throttle is opened when the plane is in level flight, several things happen. The engine speeds up, the plane increases speed, and therefore air is forced over the top of the wings at a greater speed. As a result, the Bernoulli effect is increased, the lift becomes greater than the weight, and the plane begins to climb. If, on the other hand, the plane slows down, it also goes into a downward glide. Can you explain why?

The pilot of a plane, unlike the driver of an automobile, must understand exactly how and why the various parts of his plane operate. The motion of a plane is much more complicated than the motion of an automobile and, in addition, the pilot is responsible for the safety of the passengers. A pilot may wish to speed up his plane, climb, and turn right, all at the same time. How can he do these things? All motions

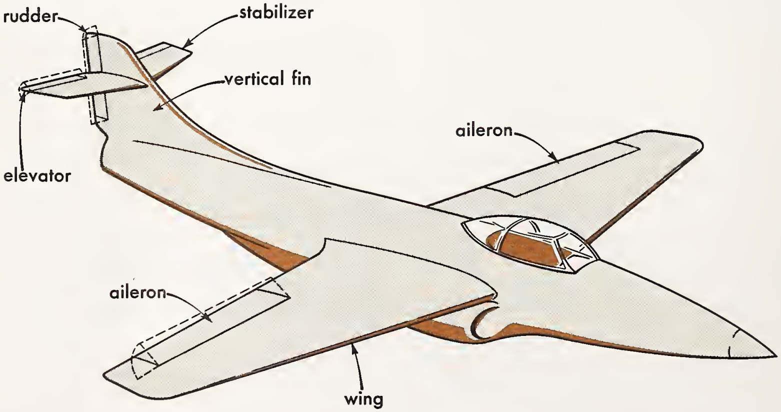


Fig. 26-10. The elevators of a plane are used for climbing; the ailerons and rudder for turning.

are controlled by four different devices: a *throttle* for changing the engine speed, *elevators* for climbing, and a *rudder* and *ailerons* for turning. Let us now examine these parts a little more closely.

The Rudder and Elevator

The rudder and elevator are at the rear of an airplane; they consist of vertical and horizontal parts. The vertical part is made in two sections, a vertical stabilizer which is fixed, and a rudder which can be moved to the right or left. The vertical stabilizer prevents the plane from veering off its course to the right or left. The horizontal part also consists of two sections—a horizontal stabilizer, which is fixed, and the elevators, which can move up or down. The horizontal stabilizer keeps the airplane in a horizontal course by counteracting the vertical drift if the tail tends to go up or down. However, before we can understand how the rudder or elevators work, we must refer to one of the three laws of motion, discovered by the English scientist, Isaac Newton, in the seventeenth century.

Newton's Third Law

Newton's third law of motion states: ***For every action there is an equal and opposite reaction.*** This law can be illustrated by several familiar examples. For instance,

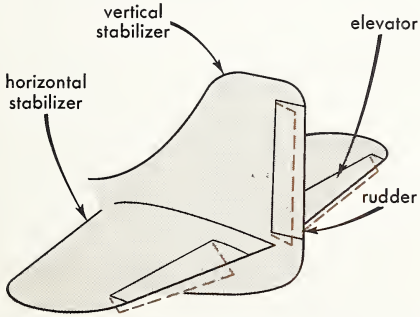


Fig. 26-12. The rudder and elevators at the rear of a plane help with the steering.

Fig. 26-11. Notice the streamlined shape of the plane; this reduces wind resistance.

suppose a rock weighing 500 pounds rests on the ground. The rock pushes against the ground with a force of 500 pounds. Then why does the rock not sink into the earth? Obviously, the earth pushes back on the rock with the same force of 500 pounds, and so it remains stationary.

Or consider the equal and opposite forces that are involved in the act of walking. In walking, we push back on the earth, and the earth pushes forward on us. Our backward push on the earth is called the *action*; the forward push of the earth on us is called the ***reaction***. Our motion in walking is therefore due to the reaction of the earth.

One other example. If you were to throw a rock over the stern of a canoe, you and the canoe would move forward. Why? The *action* is delivered by the hand upon the rock when it is thrown; the ***reaction*** is the force the rock exerts against the hand in pushing you forward. Notice that action and reaction cause rock and thrower to move in opposite directions. With these examples in mind let us now consider

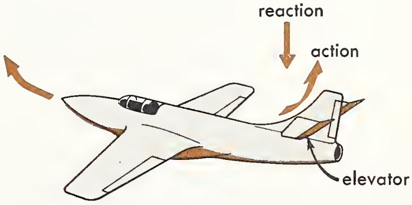


Fig. 26-13. To make a plane climb, elevators are tilted upward.

how a plane can be made to climb and turn.

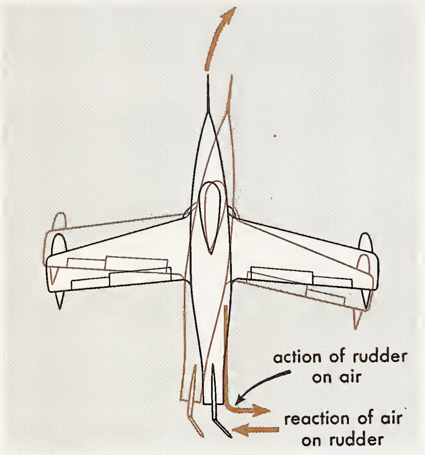


Fig. 26-14. To turn a plane to the right, the rudder is turned to the right.

To Make a Plane Climb

To make the plane climb, the pilot pulls back on the control stick or wheel, and the elevators are tilted *upward* (see Fig. 26-13). Therefore the air rushing past the elevators is also deflected upward. This constitutes the action of the elevator on air. By reaction, air pushes down on the tail of the plane, thus lifting its nose so that the plane begins to climb. When the plane has climbed to the desired height, the pilot pushes the stick or wheel forward. This depresses the elevators and, in consequence, the tail is raised. When the plane is level, he returns the wheel or stick to its normal position.

To Turn the Plane to the Right

Changing the direction of a plane is more complicated than making it climb or descend. Both rudder and ailerons must be operated in making a turn to the right or left. Let us first see how the rudder works. The rudder is controlled by a rudder bar which the pilot pushes with his feet. When the bar is pushed forward with the right foot, the rudder is turned to the right as shown in Fig. 26-14. Air is then deflected to the right by the rudder; this constitutes the ***action*** of the rudder on the air. The ***reaction*** of air on the rudder pushes it to the left. But this merely twists the plane so that it skids sideways. To prevent the skid and to complete the turn, the plane must be banked, just as a road is banked on a sharp curve to prevent an automobile from skidding. This is done by means of ailerons, which are movable sections on the trailing edges of the wings.

Ailerons are moved by a control wheel operated in the same way as the steering wheel of a car. To make a right bank, the wheel is turned clockwise. This raises the aileron on the right wing and lowers it on the left wing as shown in Fig. 26-15. How do the ailerons tilt or bank a plane? The left aileron deflects air down and therefore the reaction is to push the left wing up. Similarly, the reaction on the right wing is to push it down. Thus we see that, in turning a plane, two different processes are involved. To turn left, for instance, the rudder must be turned left and, at the same time, the aileron on the right wing must be turned down and that on the left wing up. This causes the plane to bank to the left.

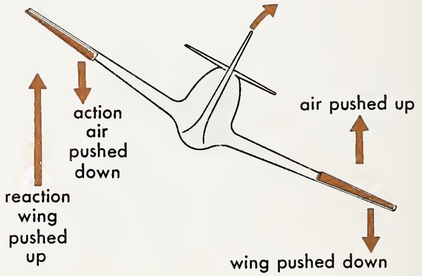


Fig. 26-15. To make a right bank, the right aileron is raised and the left aileron lowered.

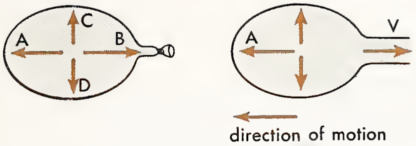


Fig. 26-16. When air escapes from the balloon at V, the unbalanced force drives the balloon forward.

The Take-off

To get the maximum lift at take-off, a plane is turned into the wind. In this way, the natural wind is added to that created by the propellers, and the speed of the air over the wing surface is thereby increased. This extra speed increases the Bernoulli lift at the time when it is most needed.

The plane taxis along the ground at increasing speed. When it reaches "rising" speed, the tail rises and the pilot tilts the elevators up by pulling back the control stick. You will recall that the effect of turning the elevators up is to push the tail down, thereby nosing the front of the plane up. As it begins to rise, the tilted underside of the wings catches the wind and, in this way, the lift on the plane is further increased.

What is Jet Propulsion?

The engine of an airplane rotates propellers, and the propellers, in turn, hurl a large mass of air backward. This constitutes the action of the propellers on the air. What is the reaction? Obviously, air pushes forward against the propellers. This is the reaction or *thrust* which drives the plane forward. Let us now turn to the waste gases that rush out of the exhaust pipe at the rear of the engine. Here is another case of action and reaction. The action is the force exerted by the engine on the waste gases thus forcing them out of the rear of the plane. The reaction is the force of the waste gases on the engine which tends to drive the plane forward. Can the reaction from the waste gases be increased enough to fly a plane, that is, to render propellers unnecessary? Let us examine this possibility a little more closely.

Experiment

26-4. Flight due to reaction

Blow up a toy rubber balloon and pinch its neck to prevent the air from escaping. Hold the balloon at arm's length and then release it. The balloon takes off "backwards" on an erratic flight and, when all the air has escaped, it falls to the ground.

What makes the balloon fly? The compressed air inside the inflated, closed balloon exerts a pressure equally in all directions as shown in Fig. 26-16. That is, pressure A is balanced by B and pressure C is balanced by D, so nothing happens. When the gas escapes from the balloon, however, a different situation exists. There is no longer a force on the balloon at B; instead the balloon pushes the gas out at V. This force is the *action*. The force A is now an unbalanced force; it is the *reaction* of the gas on the balloon. It makes the balloon move. This is how a jet engine works.

One other illustration will help before we try to build a crude jet engine. In firing a rifle, the bullet moves at great speed in one direction and the rifle recoils at a much slower speed in the opposite direction. We speak of the *action* of the bullet and the *reaction* of the rifle. Since action and reaction are equal and opposite, it is clear that the terms mean more than speed alone. Actually, action and reaction (or thrust and recoil) depend on both mass and speed. The bullet is much lighter than the rifle, and therefore the bullet travels much faster than the rifle.

A Simple Jet Engine

Consider the situation shown in Fig. 26-17. Here a fuel such as gasoline or kerosene is injected into a combustion chamber and burns. When the fuel burns, the waste gases become very hot and develop an enormous pressure. If the gases escape

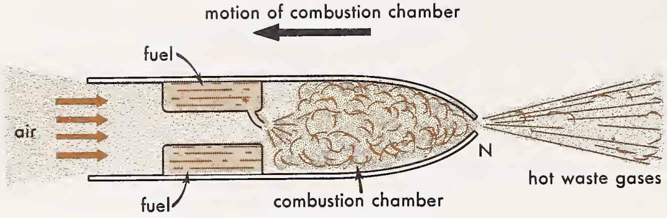


Fig. 26-17. A simple jet engine. Hot gases escape at the rear and the engine is driven forward.

through a nozzle at N, they escape as a jet stream, and the chamber moves to the left at high speed. We might say that the tank or engine is propelled by taking in cold air at the front and expelling hot gas at the rear. Notice that in this kind of engine (in jet propulsion) both oxygen and nitrogen are useful components. The oxygen, of course, is used to burn the fuel. The hot nitrogen escapes as one of the gases in the jet stream, and so increases the forward thrust on the engine. This simple device is capable of propelling jet planes at speeds higher than the speed of sound.

The accompanying crude diagram is clearly not a workable engine. How is the fuel forced into the combustion chamber? How is air forced in at the front? How is the fuel mixture lighted? These questions will be answered in the next chapter when we consider various types of jet engines.

Things to Remember

The *Wright brothers* flew the first powered heavier-than-air machine at Kitty Hawk, North Carolina, in 1903.

Bernoulli's principle states that the pressure within a fluid in motion is lower than the pressure outside the stream; and the greater the speed of the stream, the less is the pressure within it.

An *airplane is lifted* because the pressure on the upper surface of the wing is lower than that on the under surface.

A force may produce two effects in different directions at the same time. These effects are called *components of the force*.

To keep a plane in steady flight [a] the *lift* must equal the *weight of the plane*, and [b] the *drag* must equal the *thrust of the propeller*.

The motions of an airplane are controlled by its *throttle, elevators, rudder, and ailerons*.

Newton's third law of motion states that for every action there is an equal and opposite reaction.

A *jet engine* produces motion by ejecting waste gases to the rear of the engine.

Questions

Part A

1. State Bernoulli's principle.
2. What are the components of a force?
3. What are [**a**] the vertical component and [**b**] the horizontal component on an airplane wing?
4. What is meant by the terms ***lift*** and ***drag***?
5. Name the conditions that determine the amount of lift on a plane.
6. What is the function of each of the following parts of a plane: [**a**] the rudder, [**b**] the elevators, [**c**] the ailerons?

Part B

7. Explain why, in the airflow through a venturi tube, [**a**] the speed is greatest in the constriction and [**b**] the pressure is least in the constriction.
8. What causes the Bernoulli lift on the wing of a plane?
9. Two pairs of balanced forces act on a plane in level flight. Explain what this statement means.
10. What happens to a plane in flight if the throttle is opened? Why?
11. Explain how and why the operation of the elevators can make a plane glide downward.
12. How does a pilot make a left bank? Explain.
13. What is the working principle of a jet engine used for flight? Draw a diagram.

Things to Do

The Bernoulli effect

Cut a strip of thin cardboard about 6 inches by 2 inches. Make a right-angle fold about $\frac{3}{4}$ of an inch from each end and rest the folded cardboard on its two edges on a table. Blow hard through the opening between the top of the cardboard and the table top. It is difficult to lift the cardboard frame. In fact, the harder you blow the more tightly does the hollow frame seem to stick to the table. How can you explain this?

27

Jets, Rockets, and Missiles

The steam engine is a product of the eighteenth century, and the internal-combustion engine was invented in the nineteenth century. What has been done to improve transportation in the twentieth century? At the beginning of the present century the Wright brothers, you will recall, changed a glider into an airplane by means of two propellers and a small gasoline engine. Their engine was a 4-cylinder, 12-horsepower affair, not nearly powerful enough to drive present-day automobiles. So rapid has been the development in this new field that, in the short space of 60 years, the power of airplane reciprocating engines has increased from 12 h.p. to more than 3500 h.p.

Even more spectacular advances, however, have been made in a new kind of aircraft engine called a *turbo-jet*. Like the propeller-driven engine, it operates on the principle of action and reaction. A turbo-jet ejects large volumes of hot gases out to the rear and, by reaction, it is hurled forward at high speed.

The turbo-jet engine (or jet as it is commonly called) was invented less than 40 year ago. Unlike the piston engine, which was used on the ground before it went to the air, the jet engine was "born" in the air. However, it has now come down to earth in the form of a ***gas turbine*** and is being used for many purposes besides providing power for flight. No other engine has developed as rapidly as the gas turbine; it is the most versatile engine ever built.

We have already referred to the pioneering work of James Watt, the Wright brothers, and Rudolph Diesel; they all made important contributions in the field of locomotion. To these names should be added Frank Whittle, an English engineer, who invented the jet engine. At least, Whittle took out the first patent for an aerial gas turbine in 1930. But not until 1940 did the British government try out his engine in a plane. Jet engines were used by all combatants during the Second World War, but only after the war did they really come into their own. Today they are so powerful that a single jet engine can develop more than 25,000 horsepower.

Limitation in the Performance of Propeller-Driven Engines

The plane of the Wright brothers, carrying a load of one man, covered a distance of 852 feet at a speed of 33 miles per hour. Since that time, engineers have steadily improved the designs of planes to make them travel faster, go farther, and carry heavier loads. Today planes with reciprocating engines can travel at 600 miles an hour and some are capable of traveling almost 10,000 miles without refueling.

Fig. 27-1. This heavy bomber has eight jet engines, each of which can develop more than 25,000 h.p.

These engines are very durable; they can fly for about 1500 hours before they need overhauling. Their fuel consumption is relatively low, so that intercontinental flights are taken in their stride.

Propeller-driven engines, however, have a serious limitation; they cannot propel a plane much faster than 600 miles an hour, no matter how fast the propeller spins. Let us see why. The drag on a plane, due to air resistance, increases rapidly at speeds higher than 600 miles an hour and reaches a maximum when the plane travels at the speed of sound which is about 760 miles per hour at sea level. Indeed, air resistance at this speed is called the ***sound barrier***. It actually is a barrier, a "wall" of air, but once it is penetrated by higher speeds, there is smooth sailing beyond.

In order to drive planes at speeds of about 500 miles per hour, the propellers must whirl so fast that their tips rotate through the air at approximately the speed of sound. In other words, there is a "sound barrier" at the tips of the propellers even before the plane reaches the velocity of sound. Because of this increasing drag at these high speeds, a large increase in power yields only a small increase in speed. That is why a speed of about 600 miles an hour is a practical limit for propeller-driven planes. In a jet engine, however, the propeller difficulty is avoided.

A Gas Turbine

Before we can understand the operation of a jet engine, or a ***turbo-jet*** as it is commonly called, we must see how a ***stationary*** gas turbine operates. What is the essential difference between a reciprocating gas engine and a stationary gas turbine?

In a reciprocating engine the power of the hot compressed gases is used to push pistons down cylinders. The power is then transferred to a crankshaft, and the power of the crankshaft is used to do mechanical work. A small fraction of the power is lost in pushing the waste gases out of the exhaust. A gas turbine, on the other hand, is so designed that its power comes from the large volume of gas that expands to drive a turbine at high speed. Pistons and a crankshaft are, therefore, unnecessary.

In a gas turbine, the fuel burns continuously in a combustion chamber. The hot gases escape through the rear (see Fig. 27-2), where they strike the blades of a turbine wheel and rotate it at high speeds. As the gases pass through the turbine, they lose power, and when they finally reach the exhaust outlet they are almost com-

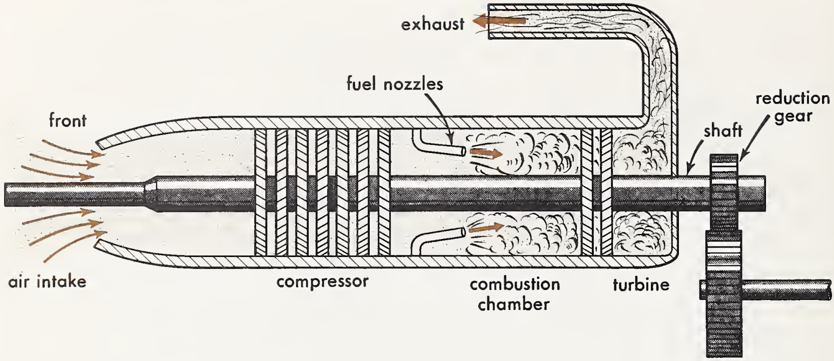


Fig. 27-2. A stationary gas turbine.

pletely spent. The turbine wheel is connected to a shaft which, in turn, operates an electric generator, or other device. In other words, a gas turbine is similar in construction to a water turbine or steam turbine. The turbine shaft is also connected with an air compressor. The rotary compressor operates like a fan, forcing large quantities of air into the combustion chamber. Liquid fuel is also sprayed into the chamber and burns in the air to give an exceedingly hot flame.

The engine must be started by an electric motor and the fuel mixture ignited by a spark plug. However, once it is started, the fuel burns continuously so that neither the starting motor nor ignition system is needed.

Gas turbines are also being used as engines for vehicles. Here they will compete with the reciprocating steam engines and diesels. Gas turbines are much lighter than diesels and have very little vibration. However, their fuel consumption is very high so that, even though they burn the cheapest fuels (such as residual oil) their fuel cost is higher than for diesels. Nevertheless, gas turbines are now being used on some ships, and working models of gas turbines have been used to propel automobiles.

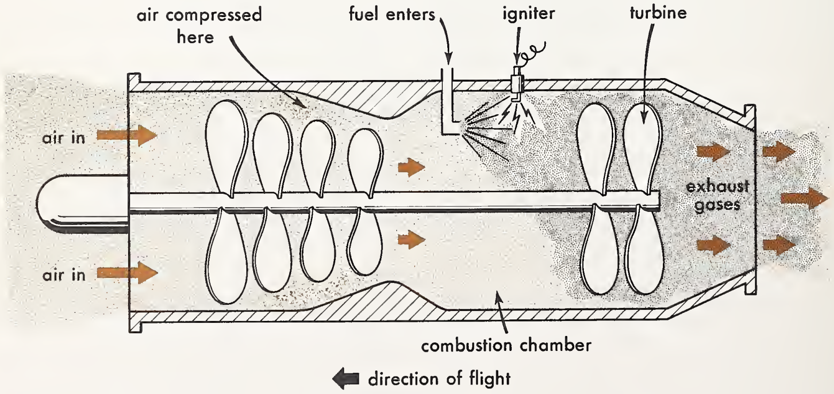


Fig. 27-3. A turbo-jet engine is used to propel aircraft.

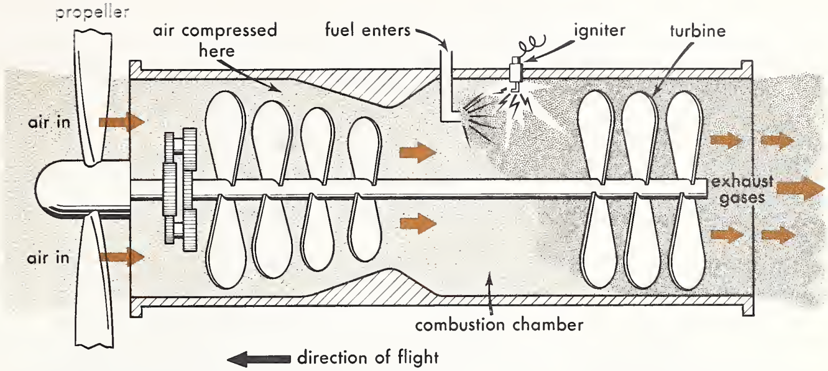


Fig. 27-4. A turbo-prop engine uses propellers to drive a plane, but the propellers are driven by a turbine, not a piston engine.

A Turbo-Jet Engine

A turbo-jet, used to propel aircraft, is similar in principle to a stationary gas turbine. The main difference between them is the way the power of the products of combustion is used. What is this difference? You will recall that in a stationary turbine nearly all the power of the hot gases is used to rotate a turbine wheel whose shaft is attached to an external machine, and little power is left in the exhaust gas. In a jet engine, however, only enough power is taken from the hot gases by the turbine wheel to drive the compressor. Therefore, the exhaust gases leave the turbine at very high velocity. These high-speed gases (which contain most of the power of the burning fuel) are directed through a large nozzle in the rear of the plane and, by reaction, the plane is thrust forward.

There are several kinds of gas turbines, such as turbo-props and turbo-jets, used in aircraft. A *turbo-prop* engine uses propellers to drive a plane, but the power to turn the propellers comes from a turbine, not from a piston engine. However, a ***turbo-jet*** engine is most commonly used to power jet planes; it is the power plant which has driven planes at speeds greater than the speed of sound. As already stated, the combustion chamber is a roaring inferno. The forcing out of high-speed waste gases at the rear of the plane constitutes the *action*; the forward thrust of these gases against the inside of the engine is the *reaction*. That is why jets operate best at high altitudes of 40,000 to 50,000 feet. The higher the altitude, the thinner the air, and therefore the less is the opposition to the outward flow of exhaust gases, and, moreover, the less is the air resistance or drag on the fuselage. Or, stated another way, the higher the altitude, the greater is the speed of the exhaust gases and, as a result, the greater is the forward thrust of the engine.

Comparison of a Jet Engine and a Piston Engine

Let us now compare the operation of a jet engine and a piston engine. In a jet engine, heat is transformed directly into the work of propelling a plane. All the intermediate steps of a piston engine are eliminated–pistons, drive shaft, cams and valves, propeller, and ignition system. A jet engine, therefore, is much simpler than a piston or reciprocating engine and, since a jet engine does not have to transfer the power of expanding gases to a drive shaft, it is more efficient. The forward thrust of a jet (which depends on the mass and speed of the gases ejected) is far greater than the thrust of a propeller. That is why jets can

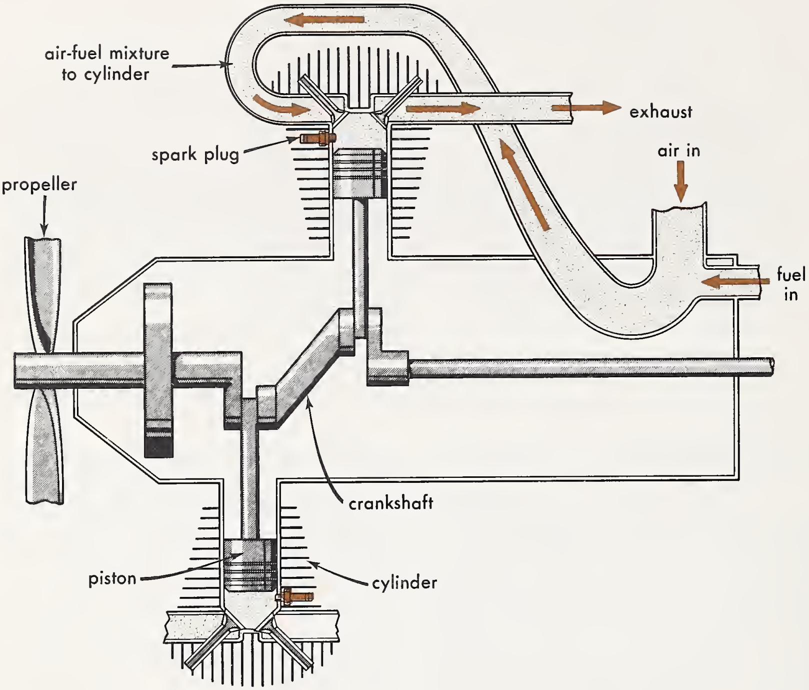


Fig. 27-5. A piston engine is more complicated than a jet engine.

break the sound barrier more easily than propeller-driven planes. Another advantage of a jet engine is that kerosene is just as good a fuel as expensive super-aviation gasoline.

The outward rush of the exhaust gases makes a terrific noise. It is one of the loudest noises that man has to cope with. Although noise does not affect pilots traveling at high speeds, operators on the ground have been permanently deafened by it. Another serious limitation of a jet engine is its heavy fuel consumption at high speeds.

A Ram-Jet Engine

Another type of jet engine is the *ram-jet*; it is mechanically much simpler than a turbo-jet (see Fig. 27-6), but far more difficult to develop as a practical engine. A ram-jet has neither compressor nor turbine and this, as we shall see, limits its use to guided missiles. If a fuel-air mixture burns in the central chamber of the ram-jet, the expanding gases escape at both ends and therefore the engine cannot start from rest. If, however, the engine is first moved at high speed, the hot waste gases are ejected to the rear, and air from the front is rammed into the chamber and compressed. It then operates like a turbo-jet and the ram-jet will be thrust forward. This means that another kind of engine is needed to get a ram-jet up to working speed; it could be launched by a rocket or a fast-moving plane.

The starting difficulty is, of course, a serious handicap and limits the uses of this kind of engine; its particular use is in guided missiles. Nevertheless, a ram-jet is, mechanically, a very simple engine. It has no moving parts to get out of order, it is

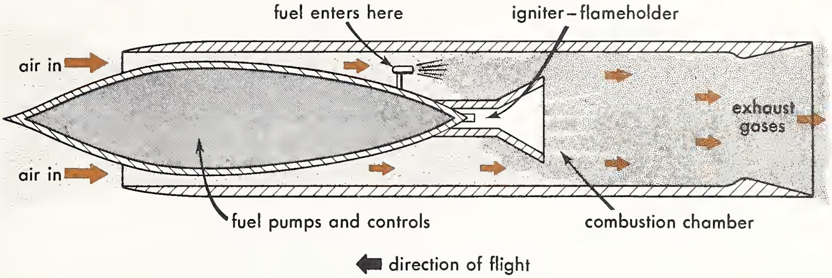


Fig. 27-6. A ram-jet engine operates without a turbine—it is the simplest kind of jet engine.

an engine of great power, it is economical to run, and it is easy to keep in good condition.

Aeronautical engineers believe that ram-jets may soon be applied to heavily laden cargo planes. These cargo planes would be given a fast take-off by rockets; turbo-jets would carry them to cruising altitudes, and then ram-jets would take over and propel them through the sound barrier. It can safely be predicted that the ram-jet will be an engine of the future.

Rockets

Rockets have been used for centuries. In the nineteenth century, particularly, they were used in warfare, in fireworks, and for many peaceful purposes. For instance, rockets were used to carry lines to stricken ships (as they still do) and to carry cables across impassable gorges as the first step in bridge building. In the War of 1812, a rocket barrage enabled the British to capture the city of Washington; in 1814, however, a similar attack against Fort McHenry, outside Baltimore, was unsuccessful. The author of "The Star-Spangled Banner" watched this rocket attack on the defences of Baltimore and referred to it in the anthem:

And the rockets' red glare, the bombs
bursting in air
Gave proof through the night that our flag
was still there.

A rocket has an exceedingly simple but efficient mechanism. Solid fuel such as smokeless powder is firmly packed in a tube and a hole is made in the powder at the rear. This hole, which is the combustion chamber, becomes enlarged as the powder burns. The larger the hole, the greater is the rate of burning and, therefore, the faster the rate at which the waste gases are expelled from the rear and, in consequence, the greater is the forward thrust.

At the turn of the century, improvements in artillery rendered rockets out of date and they were not used in World War I. During World War II, however, rockets were further developed and used for many military purposes. One of the simplest rocket devices of World War II was a "bazooka," used chiefly for attacking tanks. It consisted of a light, thin-walled metal tube open at both ends. The shell and rocket formed a single unit–a high-explosive shell attached to a solid propellant was placed in the rear end of the tube. The propellant was electrically ignited, a blast of hot gases escaped through the rear of the tube, and the shell was driven forward toward its target. The arrangement is shown in Fig. 27-7. As the rocket (shell and propellant) traveled down the tube the charge was burned up, so that the flight of the shell depended entirely upon this brief but powerful initial thrust.

A soldier firing the bazooka supported it on his shoulder. He felt no recoil because

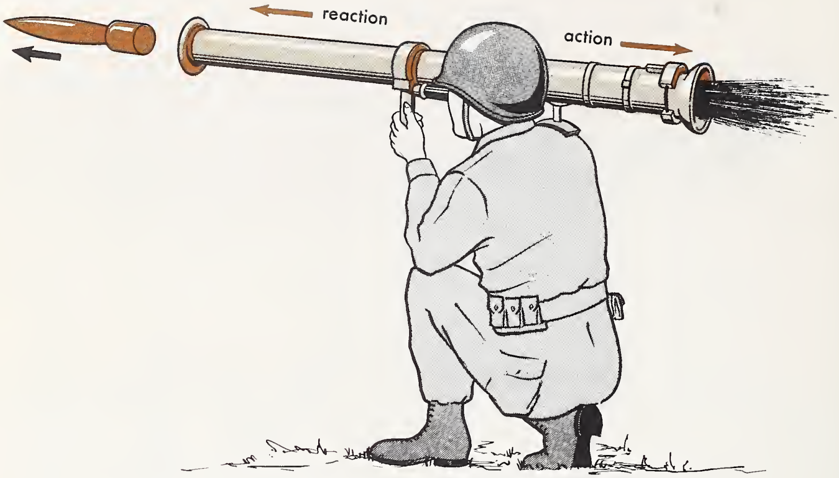


Fig. 27-7. In a bazooka, hot gases are ejected and, by reaction, a shell is hurled forward.

it was carried by the escaping gases and dispersed to the surrounding air. The tube served merely as a support for the rocket and an aiming device. This example shows that a rocket is really a ***reaction motor*** in which hot gases are ejected at the rear and, by reaction, the rocket recoils forward.

Rocket guns were also used on fighter planes to supplement machine guns, and they were installed on landing craft to clear the beaches before an invasion. Rockets were also used as auxiliary engines to help aircraft take off from short runways, such as the deck of an aircraft carrier. These rockets were attached to the underside of the wings. When the charge was ignited, hot waste gases rushed through the rear nozzles, thereby giving the plane enough extra forward thrust to ensure that it would become air-borne.

A Rocket Motor

A rocket motor, like a turbo-jet, can be used to propel a plane or a guided missile. In this case, a liquid fuel such as alcohol is usually used. The motor operates on the same principle as a jet engine; that is, it is propelled by the reaction of hot combustion gases. The only difference is that a jet engine uses the oxygen of the atmosphere for combustion, whereas a rocket carries its own oxidizer, such as liquid oxygen or nitric acid. Since a rocket does not depend on outside air, it can fly out of the earth's atmosphere—to the moon, for example. It is the only known device that can do this.

In principle, it is the simplest of all jet engines. There are no elaborate compressors and turbines; instead, the fuel and oxygen are pumped into the combustion chamber and ignited as shown in Fig. 27-8.

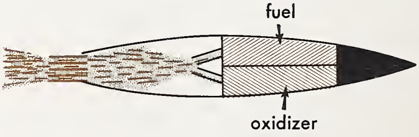


Fig. 27-8. A rocket motor is really a simple jet engine.

The temperature in the combustion chamber of a rocket is far higher than in a turbo-jet. This is because air (used in a turbo-jet) is a relatively poor oxidizer, since it consists of almost 80 per cent of nitrogen. Thus the rate of oxidation is much faster in a rocket than in a turbo-jet. The rapid oxidation rate in the combustion chamber of a rocket raises the temperature of the gas to about 3000°C. Even the exhaust gases in a rocket engine have an incredibly high temperature of 2000°C. That is why rocket-powered planes travel much faster than jet planes.

The United States government has built a number of experimental rocket planes to supply data on the sound barrier. The first of these, built in 1944, was called the X-1. It was only 31 feet long, and broke the sound barrier on its first trial mission but used up the whole of its supply of alcohol and liquid oxygen in two and a half minutes. A later model, X-2, flown in 1956, reached an altitude of more than 100,000 feet and attained a speed of almost 1900 miles an hour. This plane, like the X-1, was able to run under its own power for only a few minutes. For this reason, the small plane was carried aloft under a B-50, and then released for the speed run.

Missiles

Toward the end of World War II, the Germans used V-2 rockets against England. Armed with high-explosive warheads the rockets rose about 70 miles into the stratosphere and then plunged down upon London, 200 miles or so from the launching site, at a speed of more than 3000 miles per hour. After the war, a number of V-2 rockets were brought to the United States. The warheads of these rockets were packed with all kinds of scientific instruments needed to study the upper atmosphere. The firing of the V-2's also gave valuable data that led to the improved design of missiles.

Missiles may be driven by jet engines (turbo-jets or ram-jets) or rockets. Jet engines, of course, need atmospheric oxygen, and jet-driven missiles are often called air breathers. They can only operate within the atmosphere, and this restriction puts a limit on their speed and altitude. Rockets,

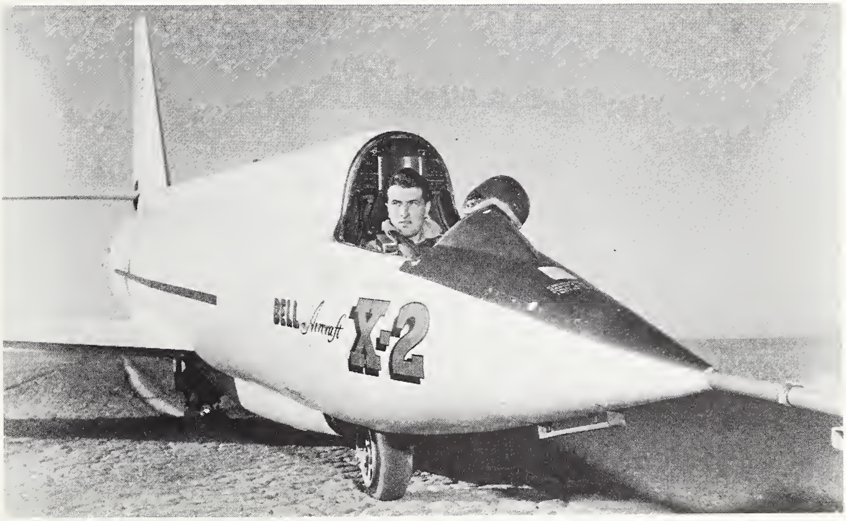


Fig. 27-9. This experimental rocket plane has traveled at almost 2000 miles an hour.

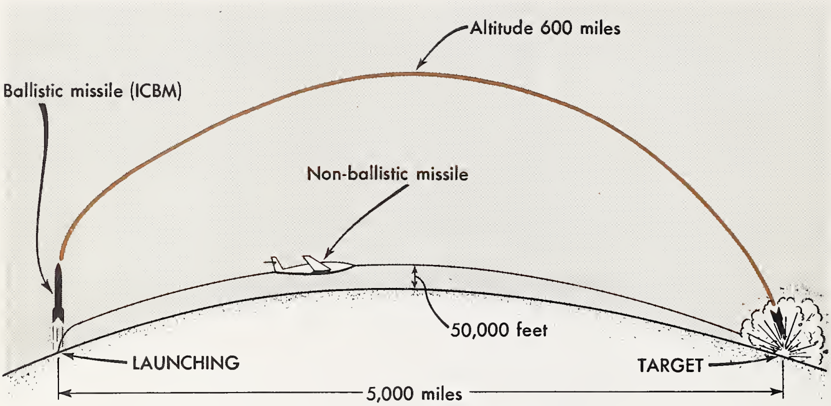


Fig. 27-10. A ballistic missile escapes from the earth's atmosphere; a guided missile stays within the atmosphere.

on the other hand, carry their own oxygen and, in consequence, they can travel beyond the atmosphere. Since rockets at high altitudes are almost free from air resistance, they also travel at far greater speeds than jet-driven missiles.

Fuel for Missiles

Rockets use various propellants; in a V-2, for example, alcohol and liquid oxygen were used. Fuel and oxidizer are kept in separate tanks. They are pumped into a combustion chamber where, upon contact, they explode and flames escape from the exhaust with a deafening roar. By reaction the rocket begins to climb, slowly at first, then faster and faster. Why the increase in speed? As the rocket rises it enters thinner air. Hence, air resistance diminishes, and consequently the exhaust velocity increases so that the reaction lift becomes greater. Rockets have enormous appetites: in the V-2 rocket, for example, ten tons of alcohol and oxygen were used up in about 70 seconds. A rocket, therefore, rapidly loses weight during burning and, as a result, its speed increases still more.

The thrust developed by a pound of fuel depends on the speed at which the waste gases are ejected. And this, in turn, depends upon the rate of burning and the temperature of the exhaust gases. A great deal of research has been done to improve the thrust of rocket fuels, so that today they develop millions of horsepower during the four or five minutes of burning time.

Liquid oxygen is still commonly used as the oxidizer in missiles, but more powerful fuels than kerosene have been discovered. The most significant factor in considering any new fuel is the amount of heat released when a pound of it is burned. Actually, hydrogen provides far more heat per pound than any other fuel. Hydrogen, therefore, would be an ideal fuel except for the fact that it is a gas and would take up far too much space in a rocket. Many elements combine with hydrogen to form combustible liquids. Kerosene and gasoline are in this category. In forming these substances, hydrogen combines with carbon. If light elements such as lithium, beryllium, or boron are used instead of carbon, the thrust of the liquid propellant is much improved. One of the most promising of the new liquid fuels is obtained by combining hydrogen with boron (obtained from borax); still another is dimethylhydrazine $(CH_3NH)_2$.

Solid propellants, which have some advantages over liquids, are also being actively developed. They can be prepared

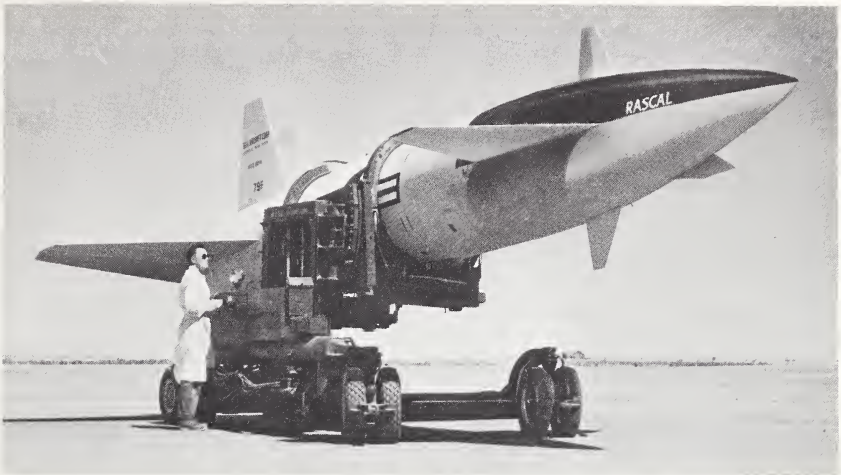


Fig. 27-11A. A guided missile.

and mixed beforehand. That is, oxidizers like potassium perchlorate ($KClO_4$) or ammonium perchlorate (NH_4ClO_4) can be mixed with a suitable fuel in the factory, thereby eliminating the need for complicated fuel pumps in the rocket itself. Moreover, solid fuels are much safer and easier to handle than liquids.

Guided Missiles

A guided missile is a rocket with a guidance system that controls its flight all the

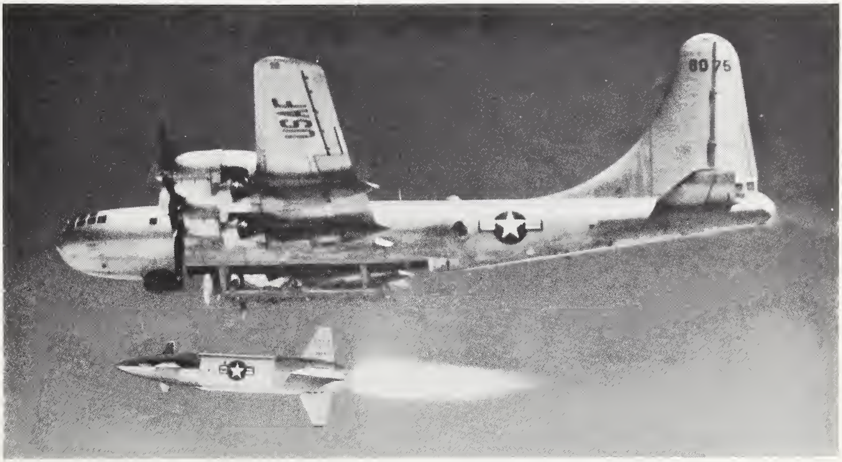


Fig. 27-11B. The guided missile, just released from the mother ship, will be directed to a target by electronic devices.

way from launching site to target. Guided missiles are the robots of the skies; they have an electronic-mechanical "brain" which can be controlled by radio, or radar, or even by other devices. To be controlled, a missile must be powered from beginning to end of its flight. At present the only suitable source of power over long distances is an air-breathing engine, like a jet. As a result, guided missiles must normally stay within the earth's atmosphere.

Guided missiles are now being employed as defensive weapons to replace antiaircraft guns which have become obsolete. Such weapons may be fired from ground or ship (surface to air) or from a plane to intercept aircraft or guided missiles (air to air). These defensive missiles have a relatively short range. Offensive missiles with a range of 5000 miles have also been tested. They have wings for lift and are really unmanned bombers. But although they travel at supersonic speeds–up to almost 2000 miles per hour–they are far slower than ballistic missiles.

Ballistic Missiles

The term ***ballistic missiles*** applies to missiles that are not guided during the greater part of their flight. Actually, the word ***ballistic*** is derived from the Greek *ballein,* "to throw," and a ballistic missile can be compared with a thrown rock. The rock is guided only during the act of throwing; once it has left the hand, it cannot be guided. Similarly, a ballistic missile receives its power and guidance at the time of firing; it can only be guided while its motors are working (that is, for three or four minutes), after which it is beyond the control of man. During this short period, however, the flight of the missile can be followed by radar and, if necessary, adjustments can be made in its course. It is therefore apparent that the flight path of a ballistic missile must be carefully computed, and must also be loaded with the right amounts of fuel mixture to carry it to its target.

Intercontinental missiles (ICBM's) have now been successfully tested. They are

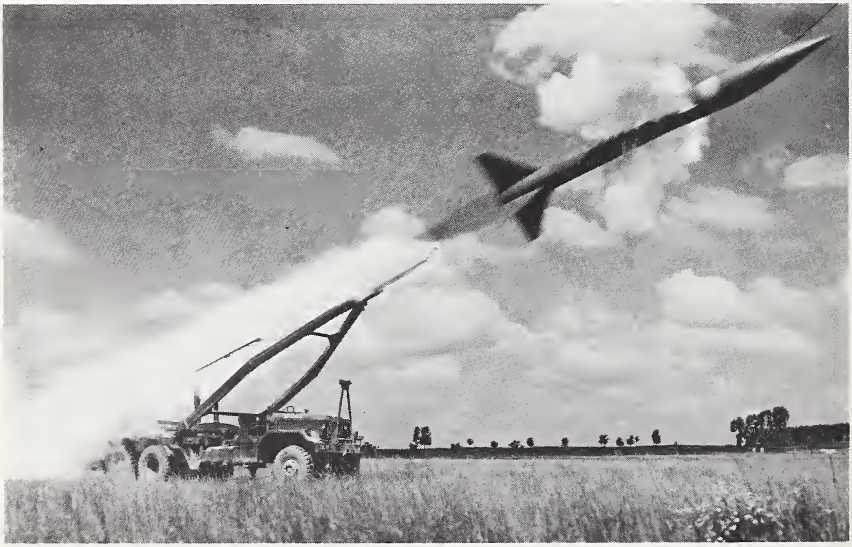


Fig. 27-12. A rocket being fired from its launcher. Rockets of this kind are being used to replace artillery.

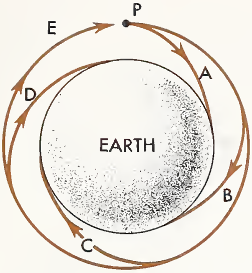


Fig. 27-13. The trajectories of objects projected from a point P above the earth. If the horizontal speed is great enough, the object will encircle the earth following path E.

monsters, almost 100 feet in length and weighing almost 100 tons. They are usually powered by liquid oxygen and kerosene, and the engines consume fuel mixture at the rate of about 1 ton per second. After the mixture has burned out the engines and tanks fall off, leaving only the nose cone (warhead) in flight. The warhead follows an elliptical path to the target, rising 600 miles or so into the stratosphere, and travels at a speed of almost 15,000 miles per hour.

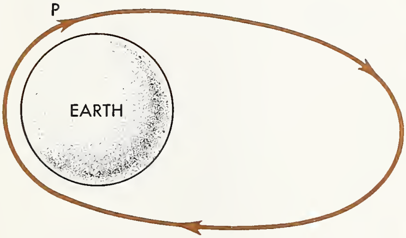


Fig. 27-14. An elliptical orbit of a satellite projected with a horizontal speed from P.

Rockets for Satellites

Any artificial satellite will stay in an orbit above the earth provided it travels at the right speed and in the right direction. Sir Isaac Newton, in the seventeenth century, explained why a satellite will stay in an orbit. As everyone knows, if you throw a ball horizontally, it follows a curved path as it falls to the ground. If the ball is thrown harder, it does not curve downward so steeply and, in consequence, it goes farther before it hits the ground. Suppose we throw an object horizontally from a very great altitude where there is so little air that air friction will not slow it down. Fig. 27-13 shows the path of such an object thrown with different horizontal speeds from a point P above the earth. The different paths (or ***trajectories*** as they are called) are marked A, B, C, D, and E. A is the path followed by an object with

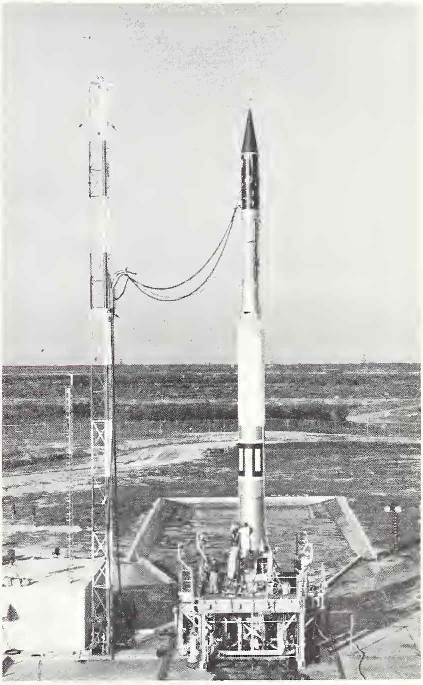


Fig. 27-15. The rocket Vanguard before launching. Its three stages are clearly visible. The mast on the left holds cables which power electronic equipment before launching.

a low horizontal speed. As the horizontal speed is increased, the object goes farther and farther around the curve of the earth (B, C, and D) until finally, with enough horizontal speed, the object will circle the earth and return to its starting point. If it is high enough so that air resistance is negligible, its speed upon returning to P will be the same as the speed with which it was originally ejected and it will go around the earth again and again. In other words, it will be in orbit.

To put a satellite in orbit, it must not only be carried by a rocket to an altitude of several hundred miles (where there is no appreciable air resistance) but the rocket must also go fast enough and in the right direction. The horizontal speed of such a rocket must be about 18,000 miles per hour (or 5 miles per second). If the satellite is not ejected horizontally at this speed when it reaches the proper altitude, it will go into an elliptical orbit (Fig. 27-14). This may bring it so close to the earth that as it circles through denser and denser air, friction will raise its temperature so that, ultimately, it becomes white hot and burns up. This has happened to quite a number of artificial satellites that have been launched. If the satellite is given enough speed it will escape from the earth and go to the moon, or to another planet, or even go into orbit around the sun.

Only the thrust of powerful rockets can lift artificial satellites to the necessary altitude and drive them at the required speed. The first American rocket to be built for this purpose was aptly called the Vanguard. The Vanguard looked like an enormous pencil–it was 82 feet long and, when loaded with propellants, weighed 11 tons. It consisted of three sections, or stages. One stage became detached as soon as its fuel was used up. The motor in the next stage then went into action. In this way, the second and third stages got a running start before their motors took over. This additive effect could be compared with the additional speed given to a ball when a ball player throws it on the run. A 3-stage rocket thus serves a double purpose. It is designed to give tremendous speed to the rocket and also to save weight. A single-stage rocket would have to be many times larger than a 3-stage rocket to reach the same speed and altitude.

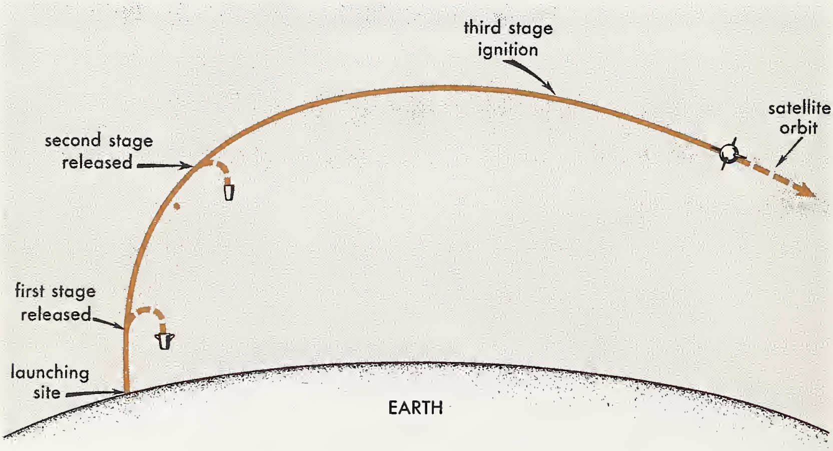


Fig. 27-16. The three stages of the Vanguard were fired in succession. The satellite separated from the third stage.

The first stage of the Vanguard was a guided rocket. It was the largest of the sections, since it had to lift the entire rocket a distance of about 40 miles against the force of gravity. Its propellant was a mixture of liquid oxygen and kerosene. The second stage contained the "brains" of the rocket. Here were housed computers, gyroscopes, and steering devices that controlled its guidance during the first two stages of its flight. The second-stage propellant, a mixture of nitric acid and dimethylhydrazine, accelerated the rocket still more and carried it almost to its orbital altitude. The third stage had a solid fuel which increased its speed to the orbital velocity of 18,000 miles per hour.

The satellite itself was in the forward part of the third stage. It was covered by a nose cone which protected it from the heat of friction as the rocket rose through the atmosphere. During the second-stage flight, air resistance was no longer a factor, and the nose was then automatically discarded. When orbital velocity was reached, the satellite was released from the third stage by a spring mechanism and, thereafter, it traveled independently in its orbit.

Things to Remember

A ***gas turbine*** burns an air-fuel mixture in its combustion chamber. The gaseous products rotate a turbine that can drive stationary engines or airplane propellers.

Gas turbines used in aircraft are [**a**] turbo-prop engines and [**b**] turbo-jet engines (or jet engines).

A ***rocket*** carries its own oxygen supply as well as fuel; therefore it can work in a vacuum.

To operate a jet or a rocket, ***gases are ejected backward, thereby driving the engine forward.***

A ***guided missile*** has an electronic-mechanical brain which directs the missile to a target.

A ***ballistic*** missile is guided only during take-off.

Questions

Part A

1. Name the principal parts of a gas turbine.
2. Name two types of gas turbines used for flight.
3. Does a plane powered with a gas turbine have a propeller? Explain.
4. Can a jet engine be used to run a sawmill? Explain.
5. Why will rockets rather than jets be used for interplanetary travel?
6. [**a**] What is a guided missile?
   [**b**] What is the missile referred to as ICBM? Is it guided?

Part B

7. Explain why propeller-driven planes cannot normally cross the sound barrier.
8. Describe the operation of a gas turbine and explain how it can be used to drive an electric generator.
9. What modifications would have to be made in the gas turbine in Question 8 if it is to be used as a jet engine?
10. What are [**a**] the advantages, [**b**] the disadvantages of a jet engine compared with a piston engine?
11. What is a ram-jet engine? What are [**a**] its advantages, [**b**] its limitations?
12. What is a rocket motor? What are the essential differences between a rocket plane and a jet plane?
13. Explain why a jet plane operates most efficiently at high altitudes.
14. What is a ballistic missile? Explain. How does it differ from a guided missile?
15. What is a 3-stage missile? What are its advantages over a single-stage missile?

Things to Do

A reaction jet motor for a boat

Punch a fine hole near the edge of the bottom of a small can that has a screw top (a tooth-powder container is suitable). Wind some stout copper wire around the can, near the top and bottom. Make "legs" out of the ends of the wires so that the can is supported by them horizontally. Half fill the can with hot water and screw on the cap. Fix a piece of candle to the base of a plastic soap dish (the "boat") and float the soap dish on water in a large pan. Light the candle and place the can (the steam boiler) over it.

The water soon boils, steam escapes through the hole, and the boat moves along the water in a direction opposite to that of the escaping steam. Can you explain why?

Acknowledgments

ILLUSTRATIONS. The authors wish to thank the various organizations which have been kind enough to supply illustrative material for use in the book.

Photos introducing the Units
  United States Air Force for Unit 1
  Imperial Oil Limited for Units 2, 3, 4, and 6
  Mount Wilson and Palomar Observatories for Unit 5

Aluminum Company of America: Fig. 1-6
American-LaFrance-Foamite Corporation: Fig. 11-12
American Locomotive Company: Fig. 15-9
American Optical Company: Fig. 23-9
American Steel and Wire Company: Fig. 1-5
Bausch and Lomb Optical Company: Figs. 21-7, 21-10, 23-1
Bell Aircraft Corporation: Figs. 27-9, 27-11A, 27-11B
The Bettmann Archive: Fig. 13-16
Bituminous Coal Institute: Fig. 12-2
Robert Bradley Company: Figs. 17-5A, 17-5B
California Institute of Technology: Figs: 22-10, 22-11
Canadian Pacific Railway: Figs. 1-8, 9-6, 24-2, 25-17
Thomas A. Edison, Inc.: Figs. 20-1, 20-4
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Ewing Galloway: Fig. 8-2, 11-5
General Electric Company: Figs. 23-12, 23-13, 24-6
General Motors Corporation: Figs. 8-4, 19-5, 25-18
Hedrich-Blessing Studio: Fig. 18-3
Imperial Oil Limited: Fig. 13-7
Johns-Manville: Fig. 16-5
Linde Air Products Co.: Fig. 19-8
E. P. Little: Fig. 22-12
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